Probing the interaction strength of the Higgs boson to the charm quark

A step towards a theory of everything

Elliot Reynolds, Chamberlain Fellow, LBNL

A note: I will pause for questions, but please also feel free to shout out

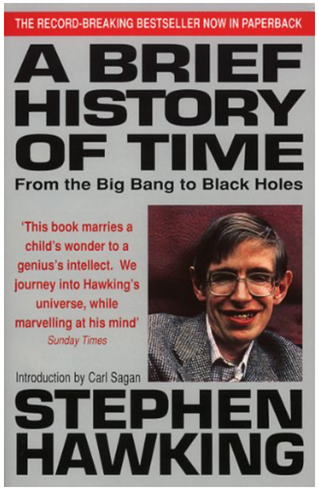
The path here

Hometown, and early education

- Shrewsbury
- The Grange Secondary School
- Shrewsbury Sixth Form College

Early interest in physics

- The **BIG** questions
  - How did the universe begin?
  - Where is it going?
  - Theory of everything?



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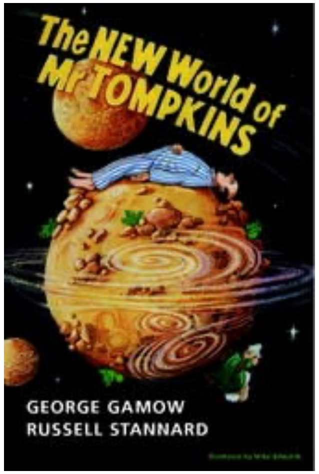

$$\Delta t' = \frac{\Delta t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

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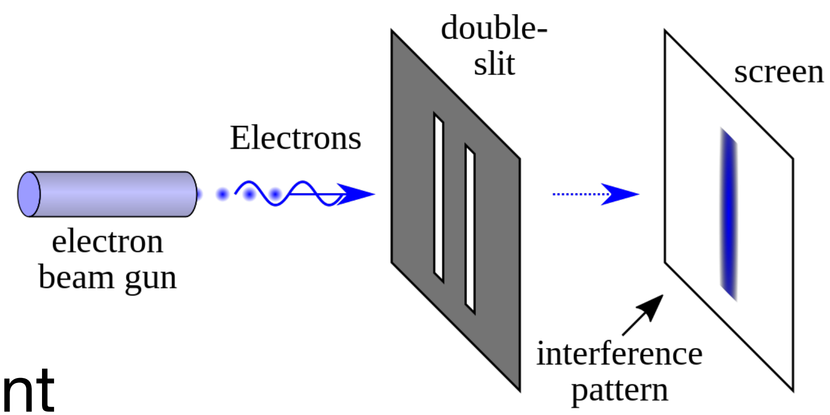
  - The double slit experiment



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- Feeling that my most basic understanding of reality was wrong

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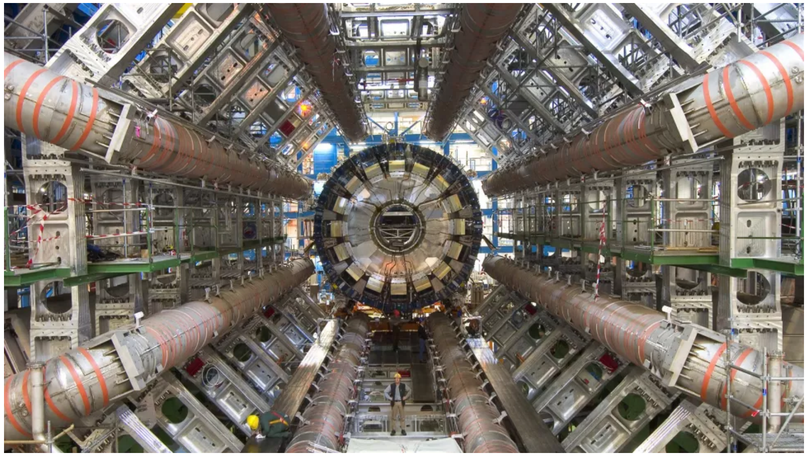
- Feeling that my most basic understanding of reality was wrong
- “Reductionism” (more to come!)

Undergraduate degree

- Most researchers complete two or more degrees
  - One (mostly) to learn about the topic
  - And one (mostly) to learn how to research the topic
- My undergraduate degree was a 4 year Master's degree in Physics at University College, Oxford

Postgraduate degree

- My postgraduate degree was a 4 year PhD at the University of Birmingham
- I spent ~1.5 years at CERN, in France/ Switzerland



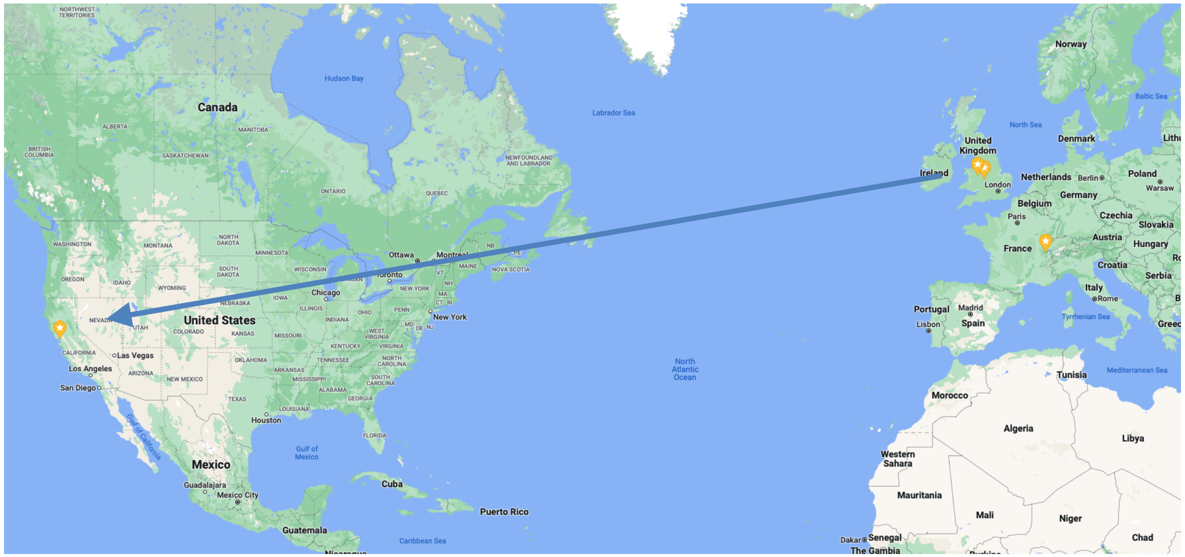
Postdoc

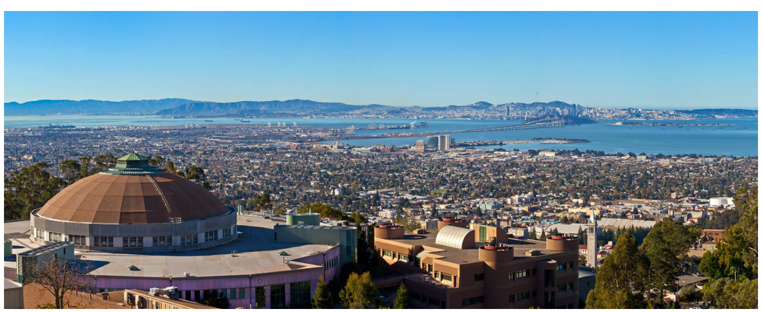
- Most graduates who want to stay on in academia do one or more “postdocs”
- Mine was also at the University of Birmingham
  - I was there for another two years
  - This may be somewhat unusual in the US
- Postdocs still work for an advisor, but are usually more independent

Fellowship

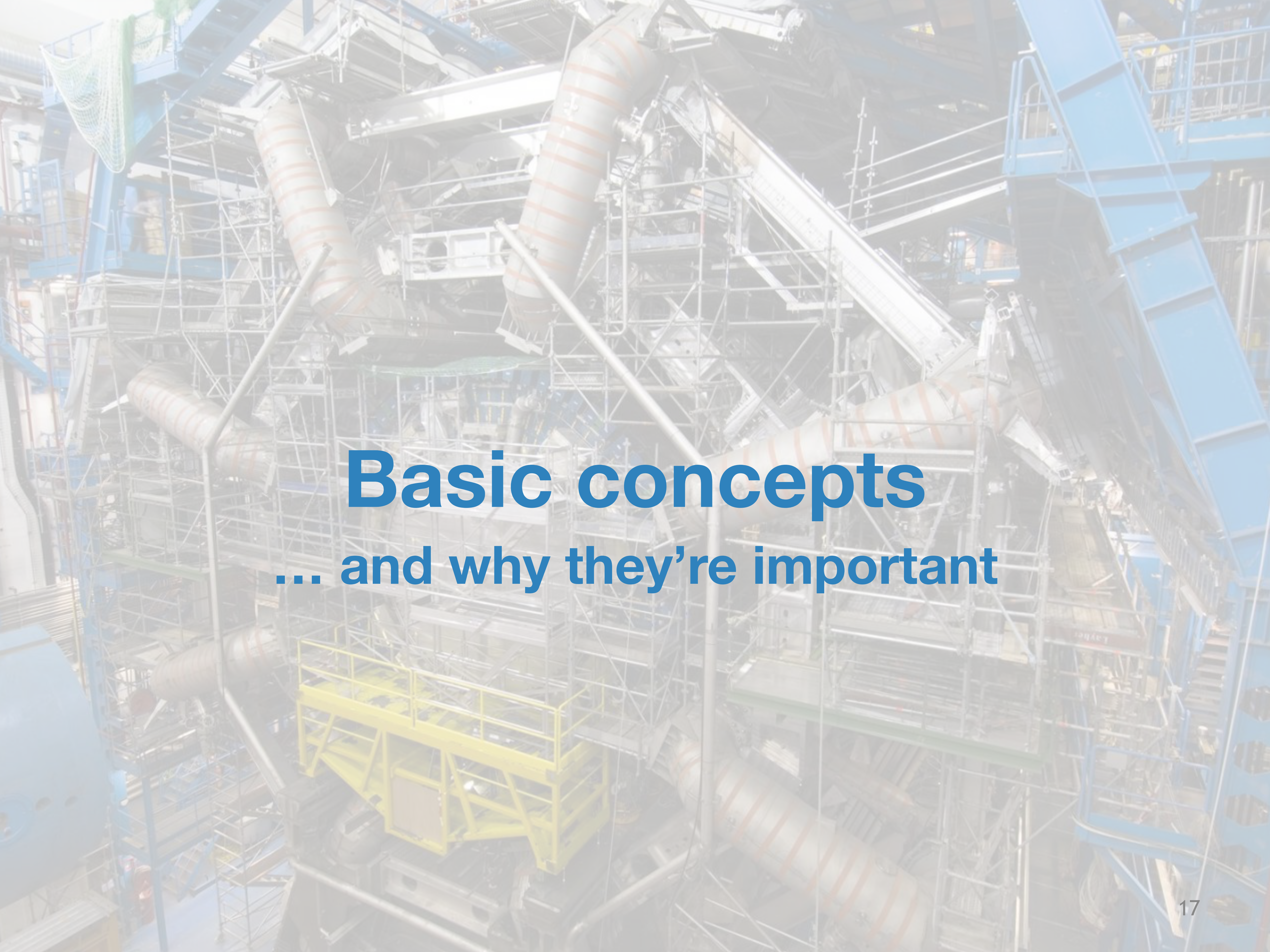
- I am now a Chamberlain Fellow at LBNL
- Fellowships are like postdocs, but often more independent, and not always with an advisor

A long journey (so far)!





Any questions?



Basic concepts

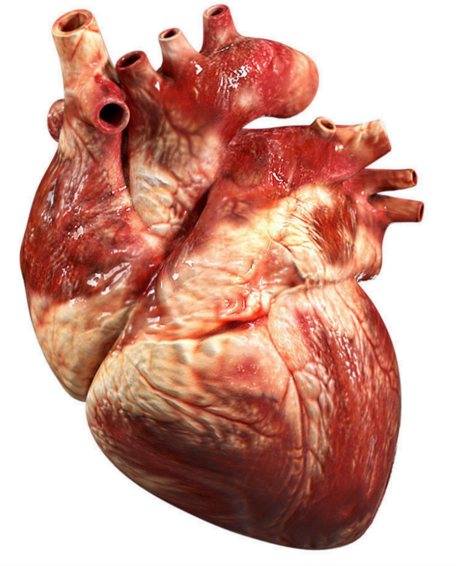
… and why they’re important

What is our world made of?

- Take this (simplified) description of a human being:

Human

Organs (+ blood, bones etc.)



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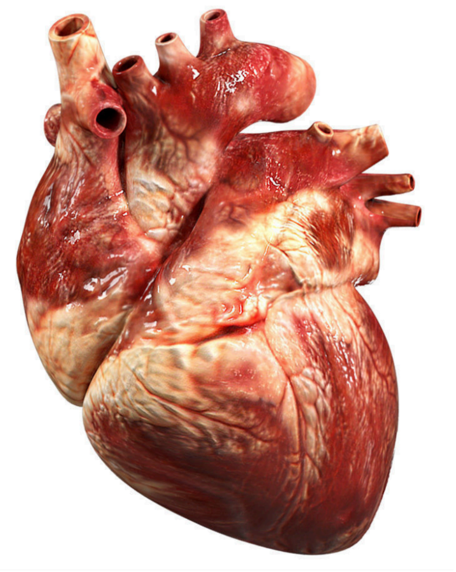
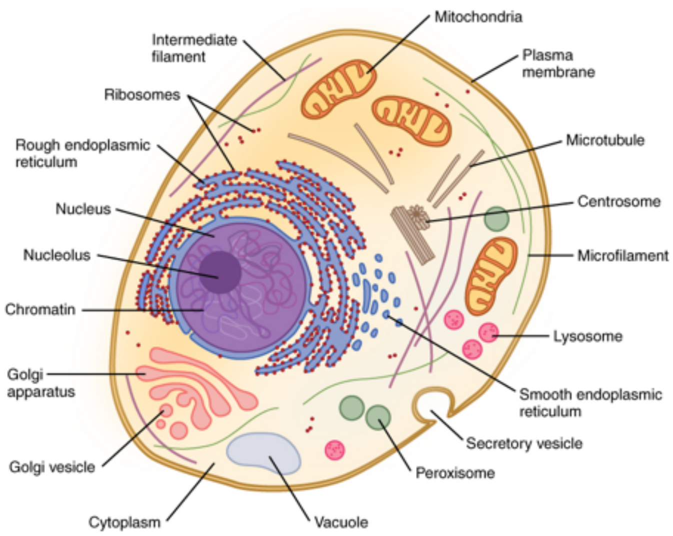


Cells



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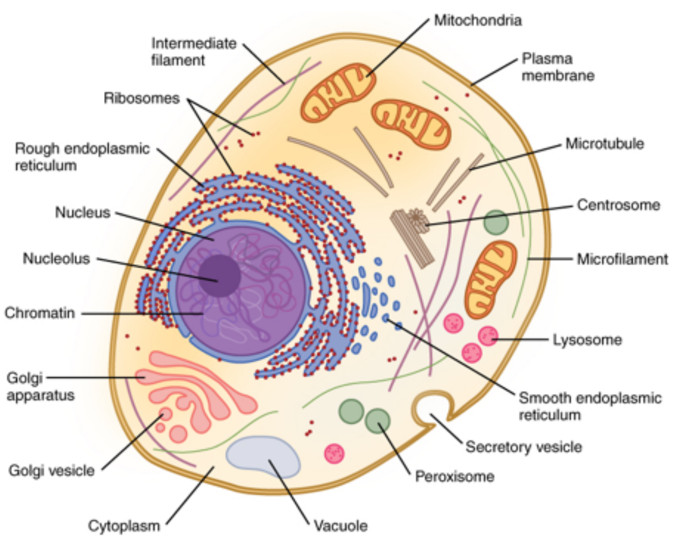
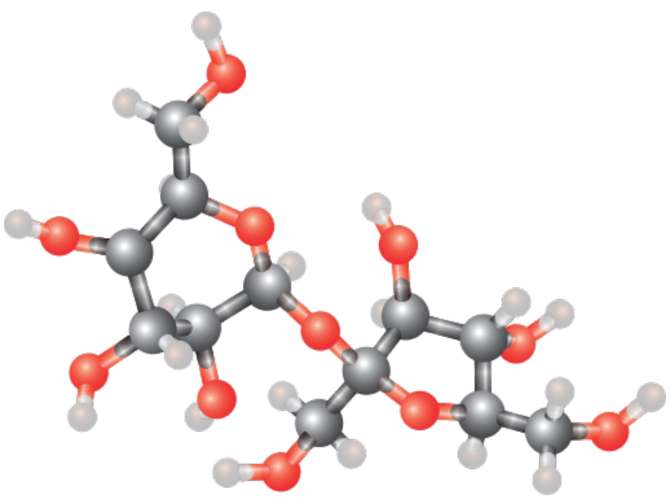


Molecules



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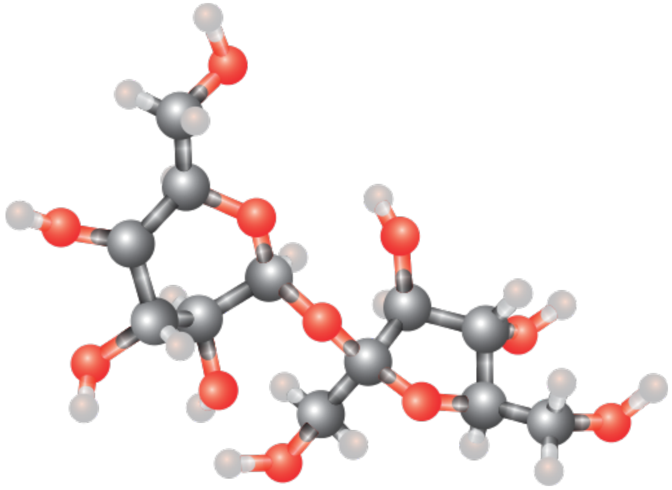
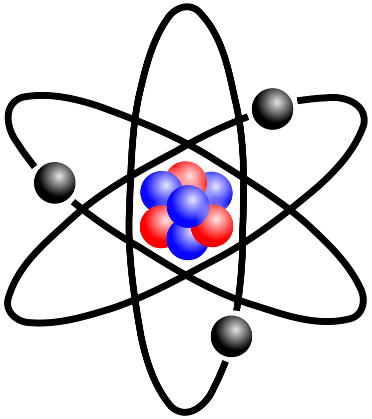


Atoms



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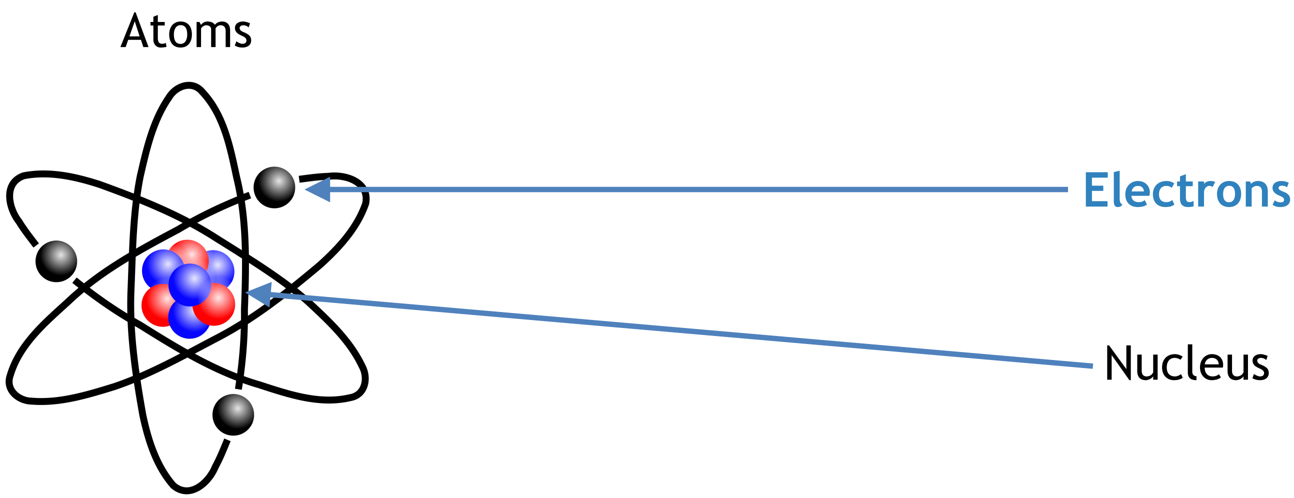

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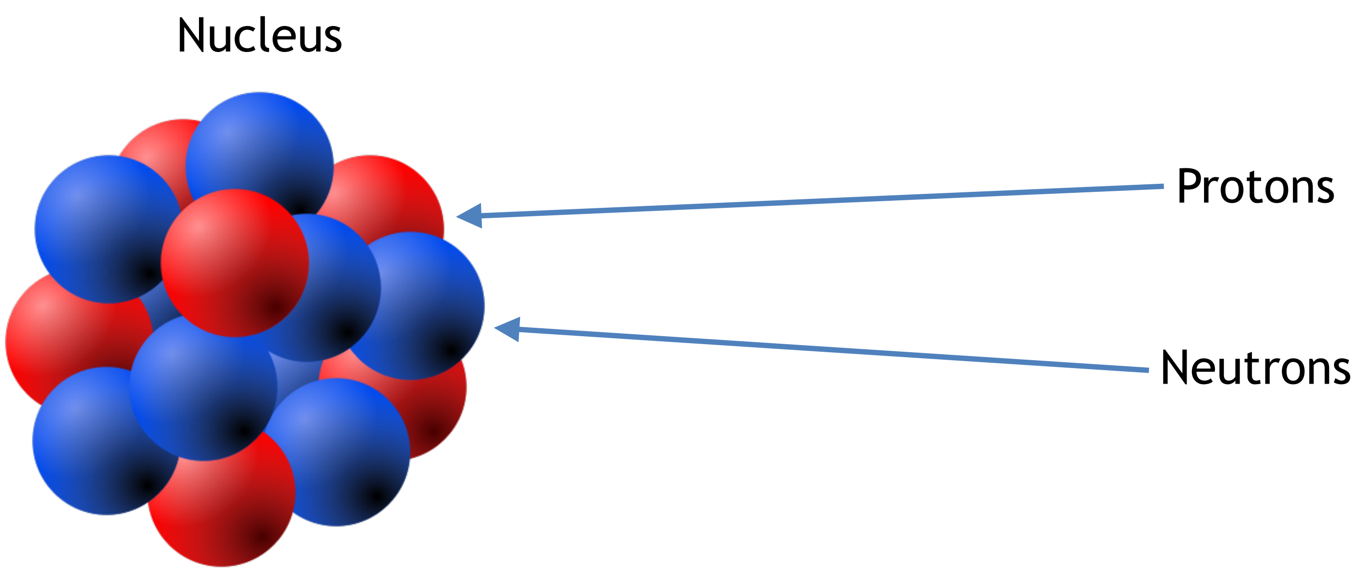

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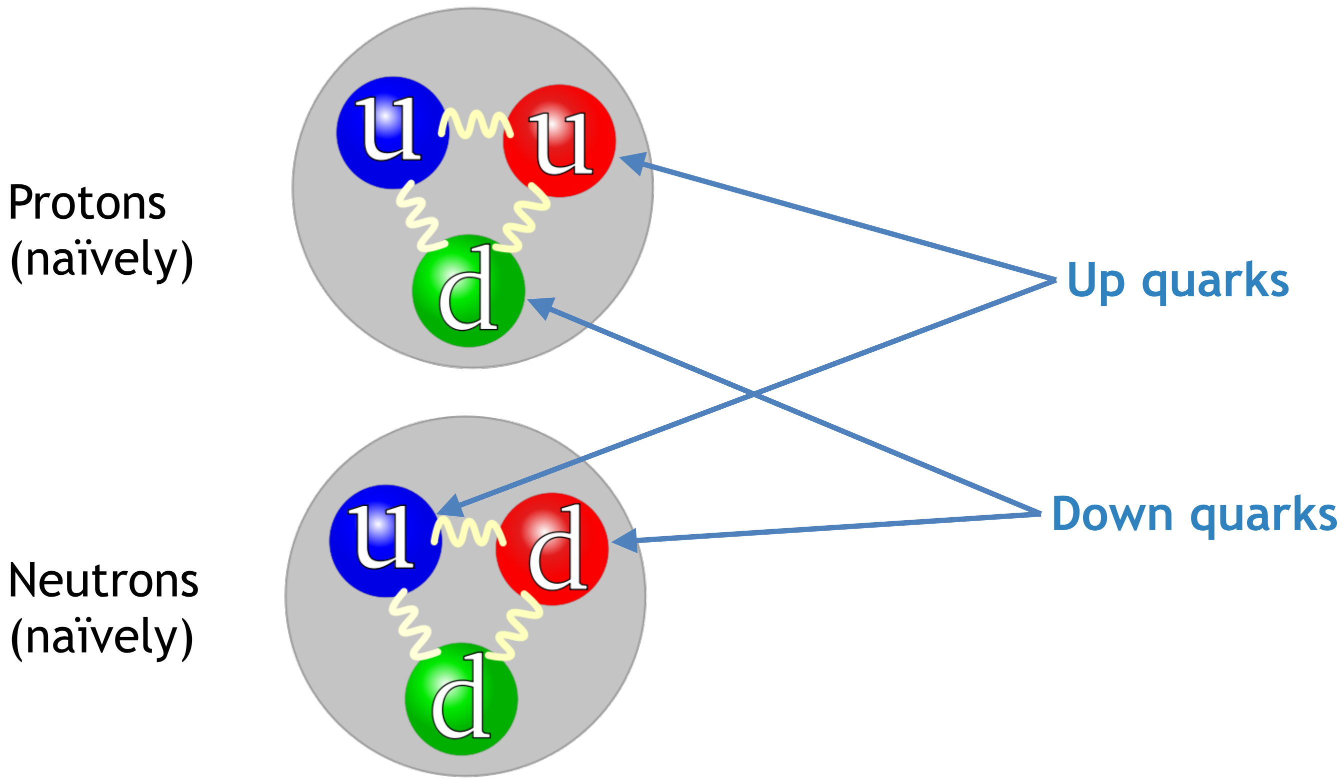
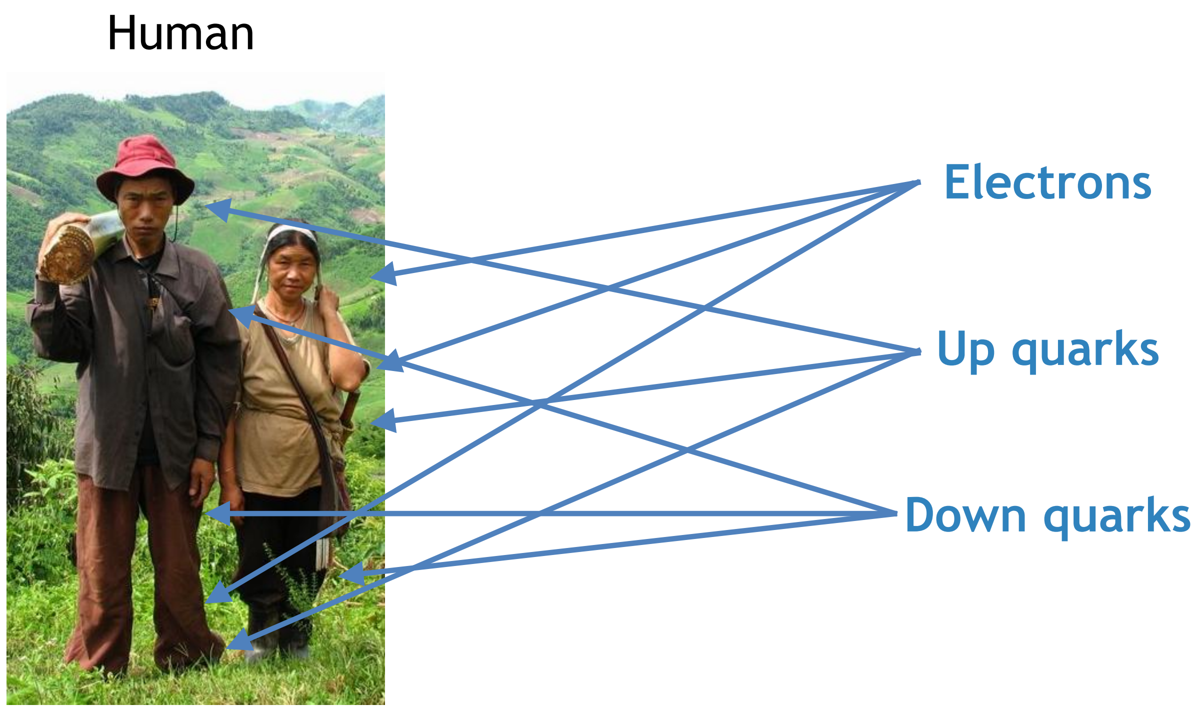


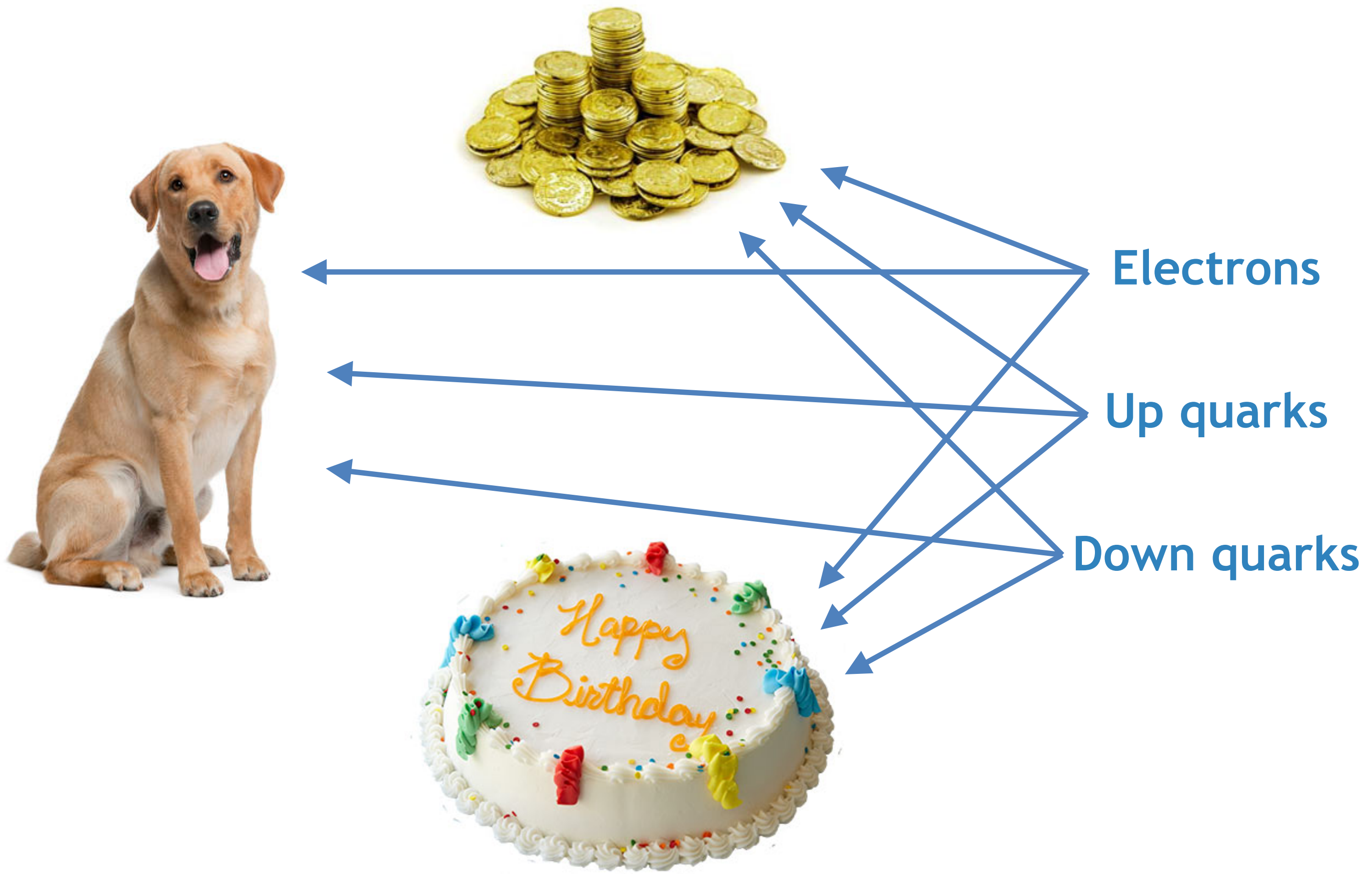
Reductionism

- Thus, a human is ~entirely made up of electrons, up quark, and down quarks

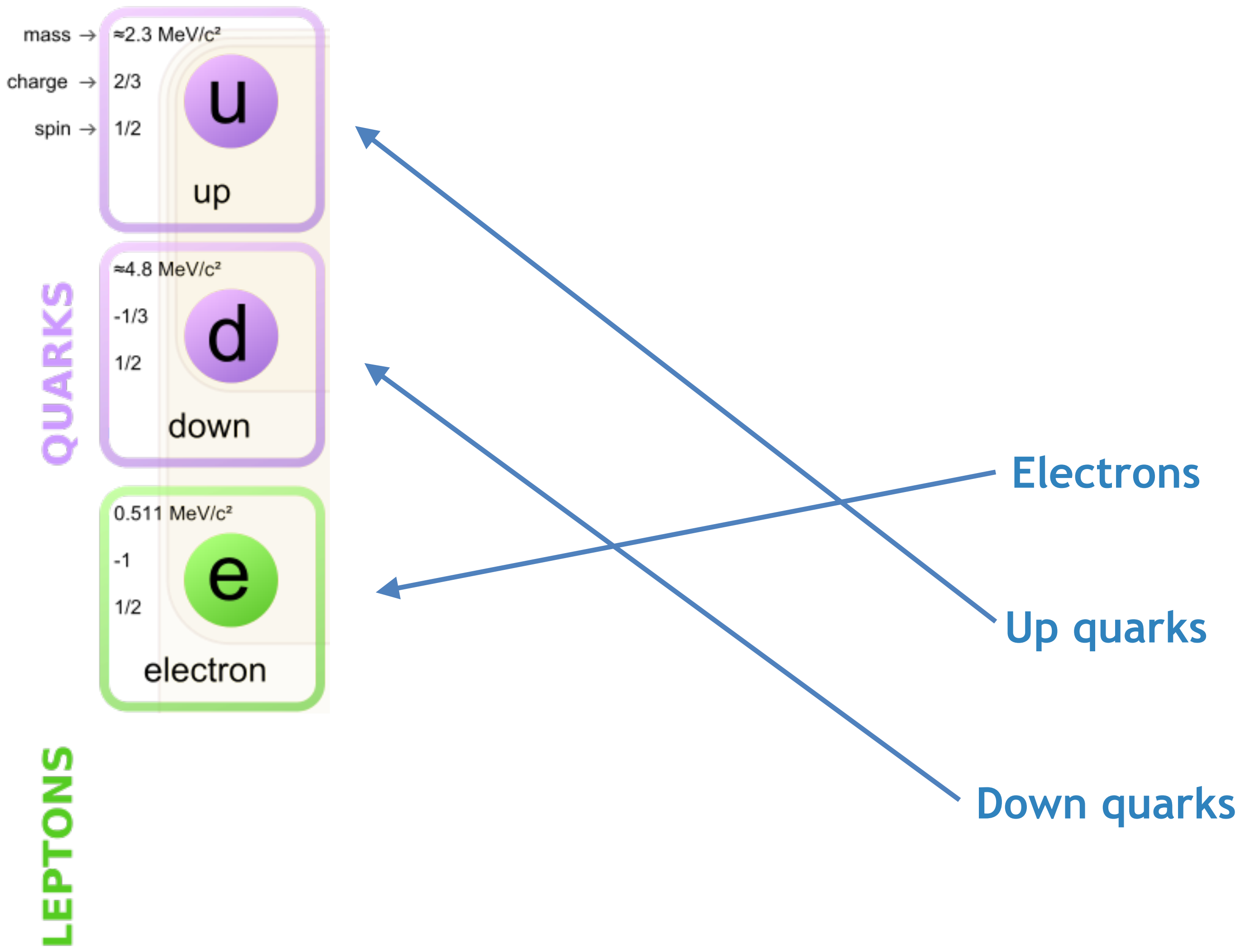


Reductionism

- But so is almost everything else:



The matter particles



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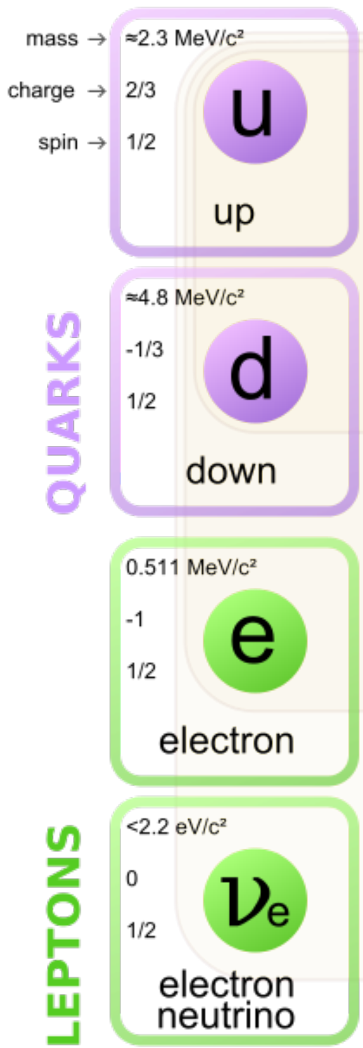
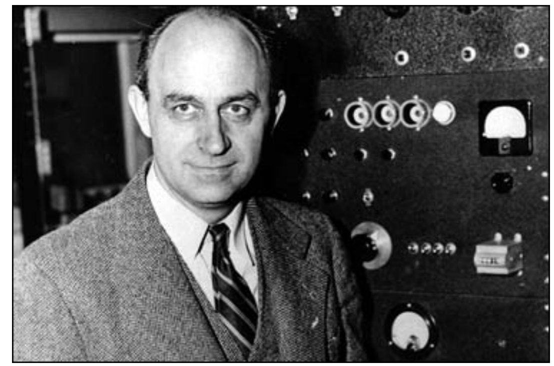
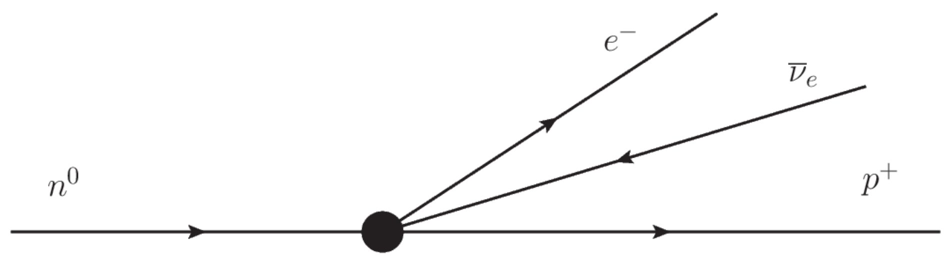


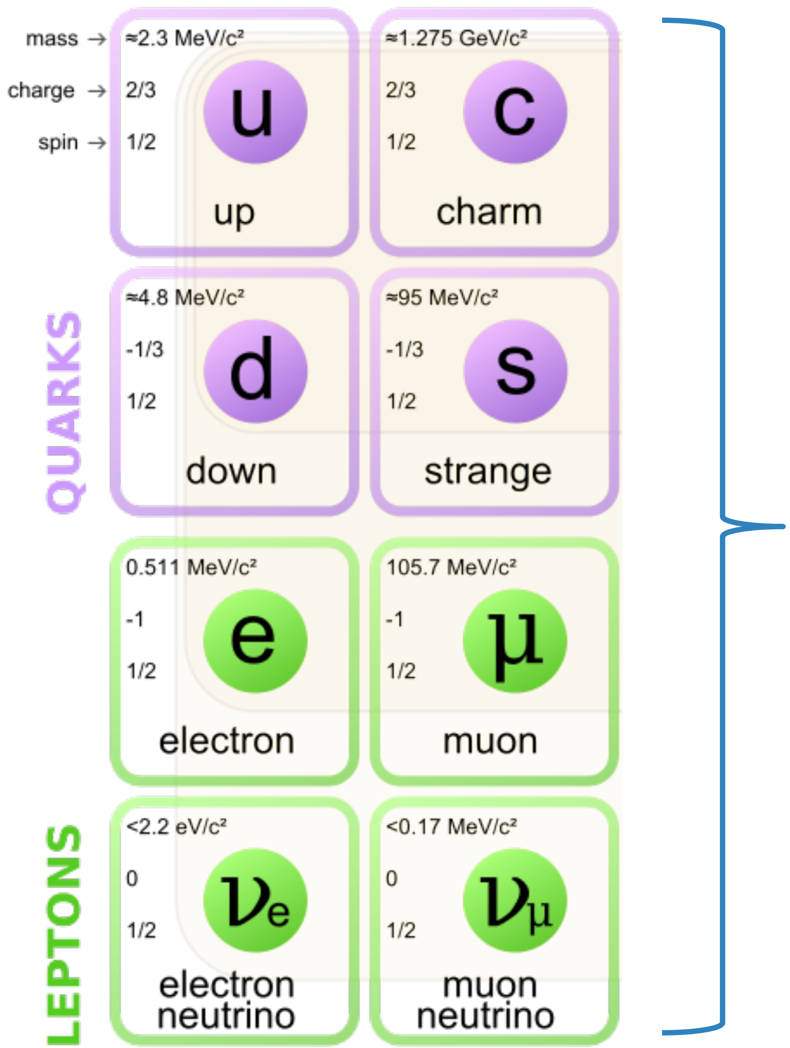


Enrico Fermi



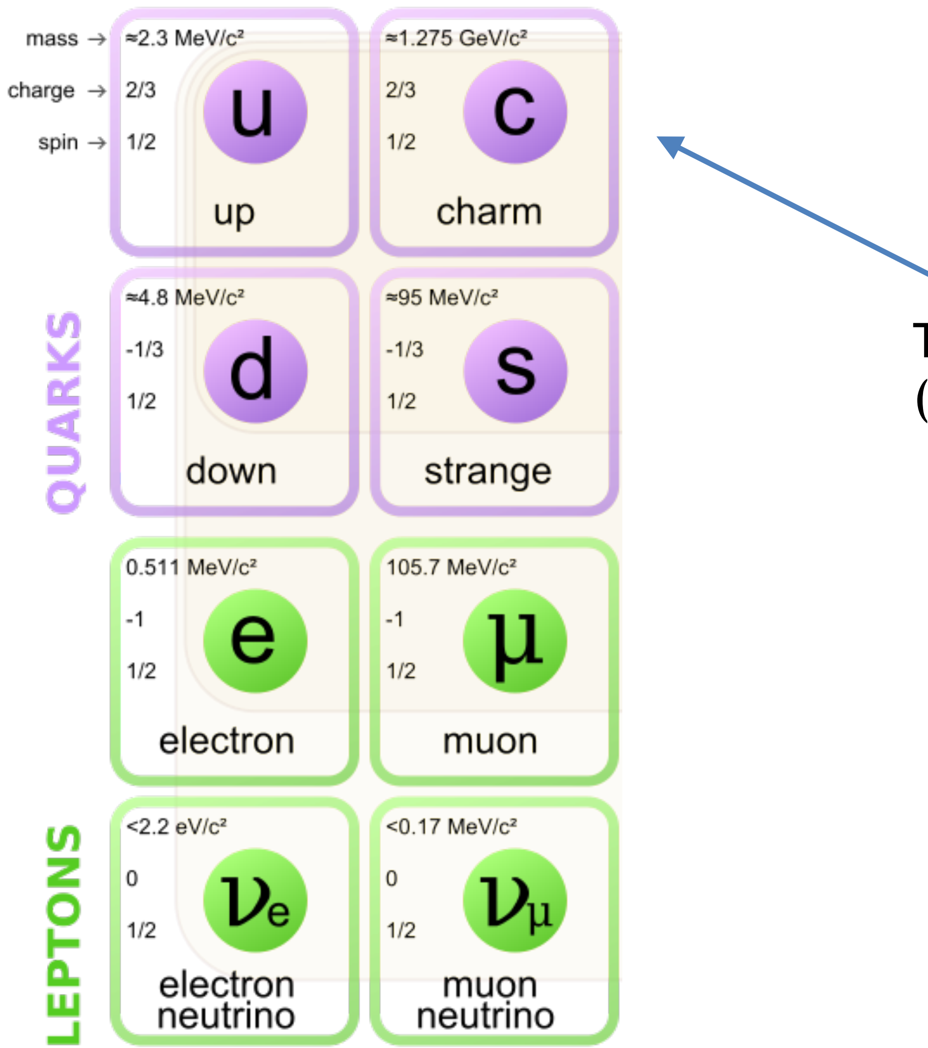
Neutrinos (the "little neutral one")

The matter particles



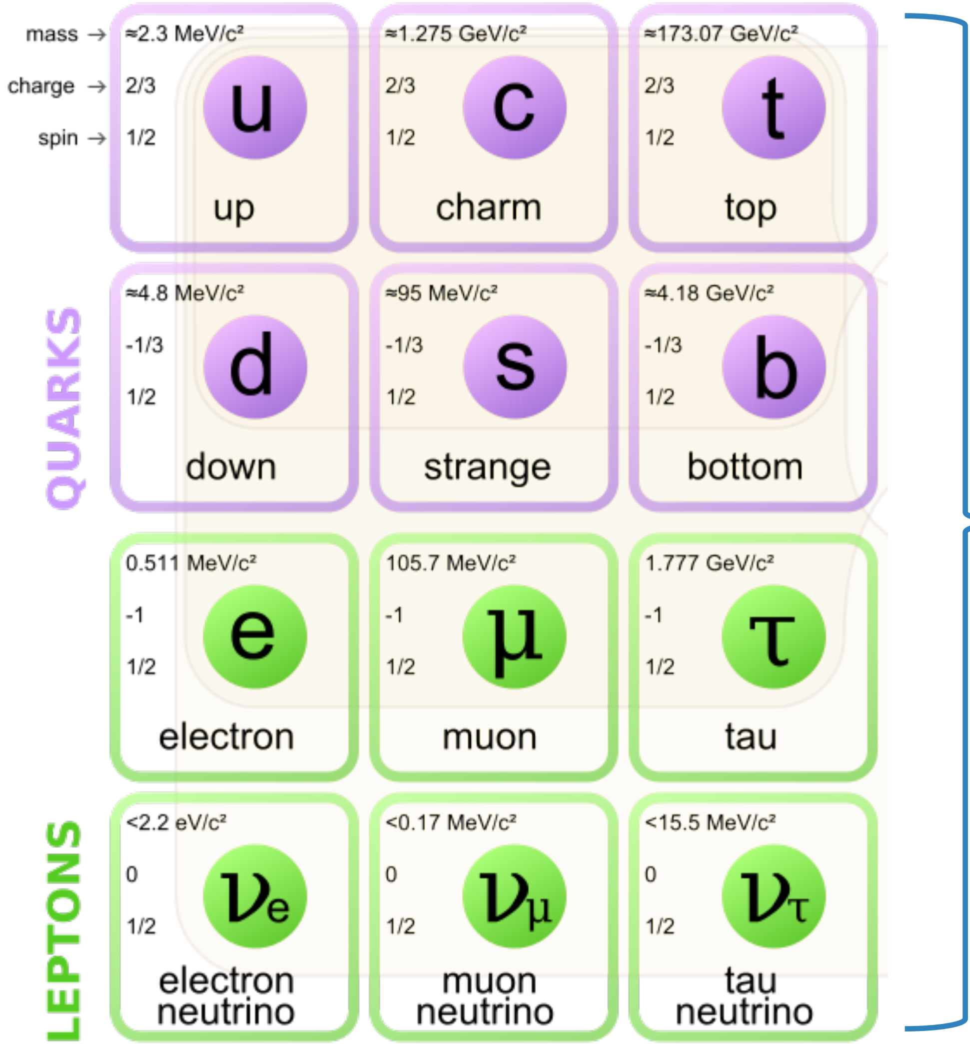
Heavier cousins
(except possibly for the neutrino)

The matter particles



The charm quark
(more on this later!)

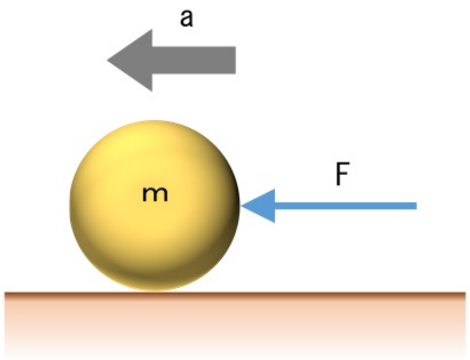
The matter particles



Even heavier cousins (except possibly for the neutrino again…)

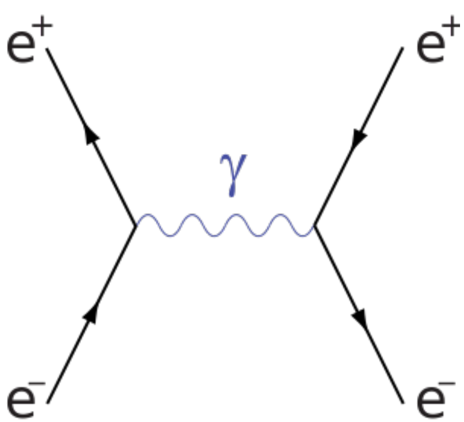
Interactions/forces

- Particle physics is not just about what the world is made of, it is also about how it works



Interactions/forces

- Particle physics is not just about what the world is made of, it is also about how it works
- It describes how reality functions on the most fundamental level through things called “interactions” or “forces”

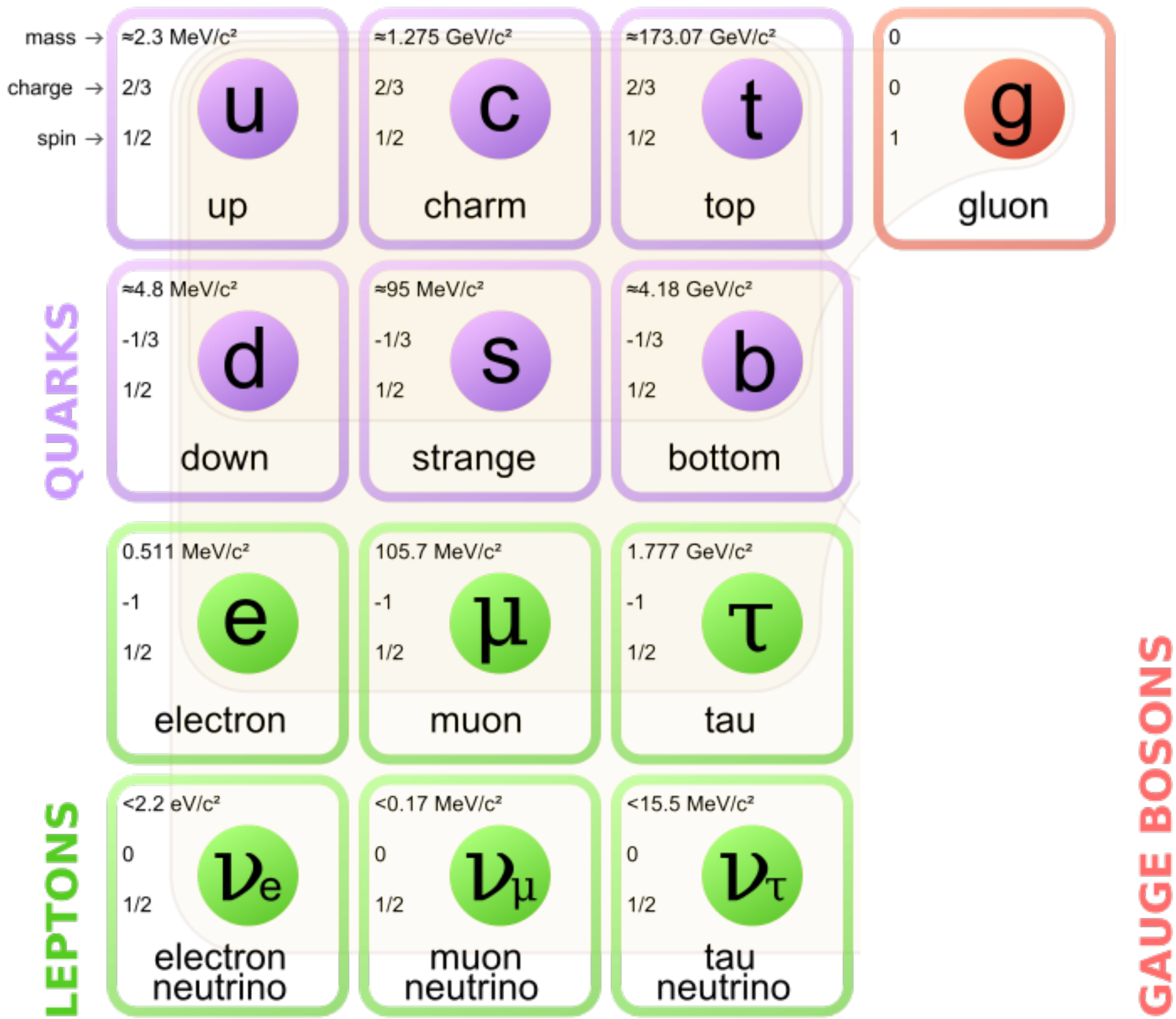


Richard Feynman

Interactions/forces

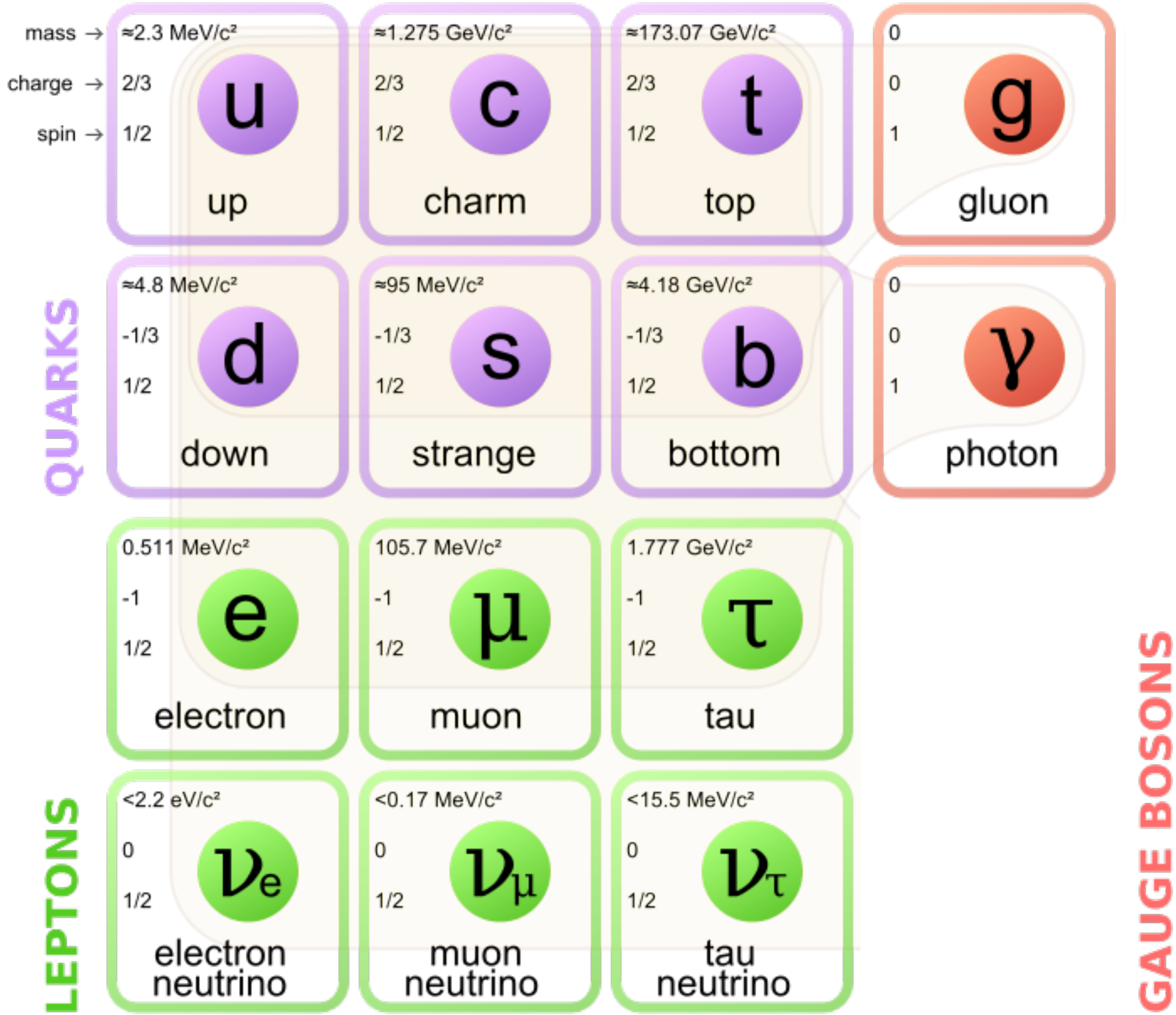
- Particle physics is not just about what the world is made of, it is also about how it works
- It describes how reality functions on the most fundamental level through things called "interactions" or "forces"
- Reality is nothing but particles and their interactions, so in principle the reason for **EVERYTHING** must reduce to particle physics
  - This is what is meant by a **Theory of Everything**!

The force carriers



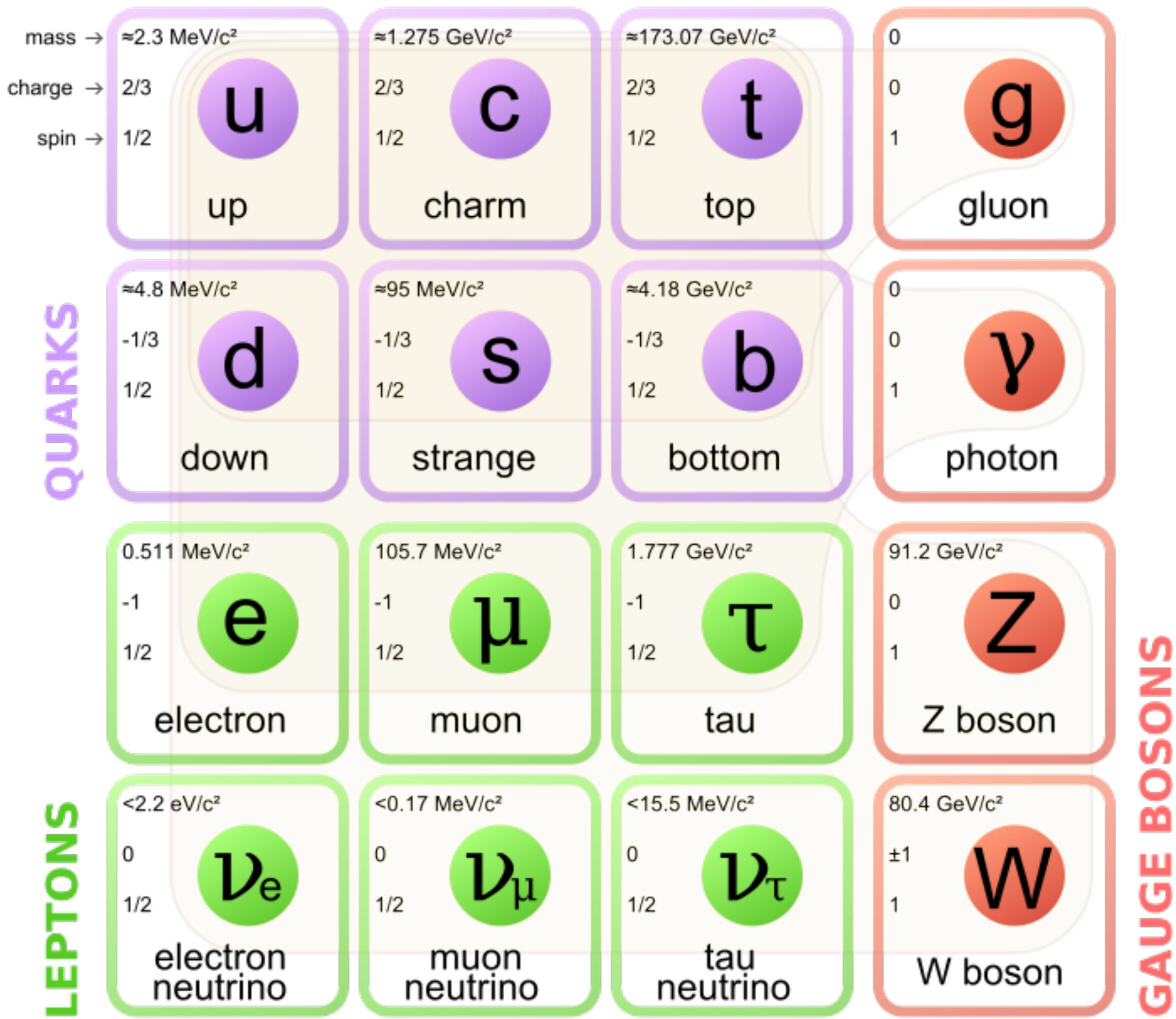
- Gluon
- Mediates the strong force
- Holds nuclei together
- Responsible for most LHC collisions
- SU(3) symmetry

The force carriers



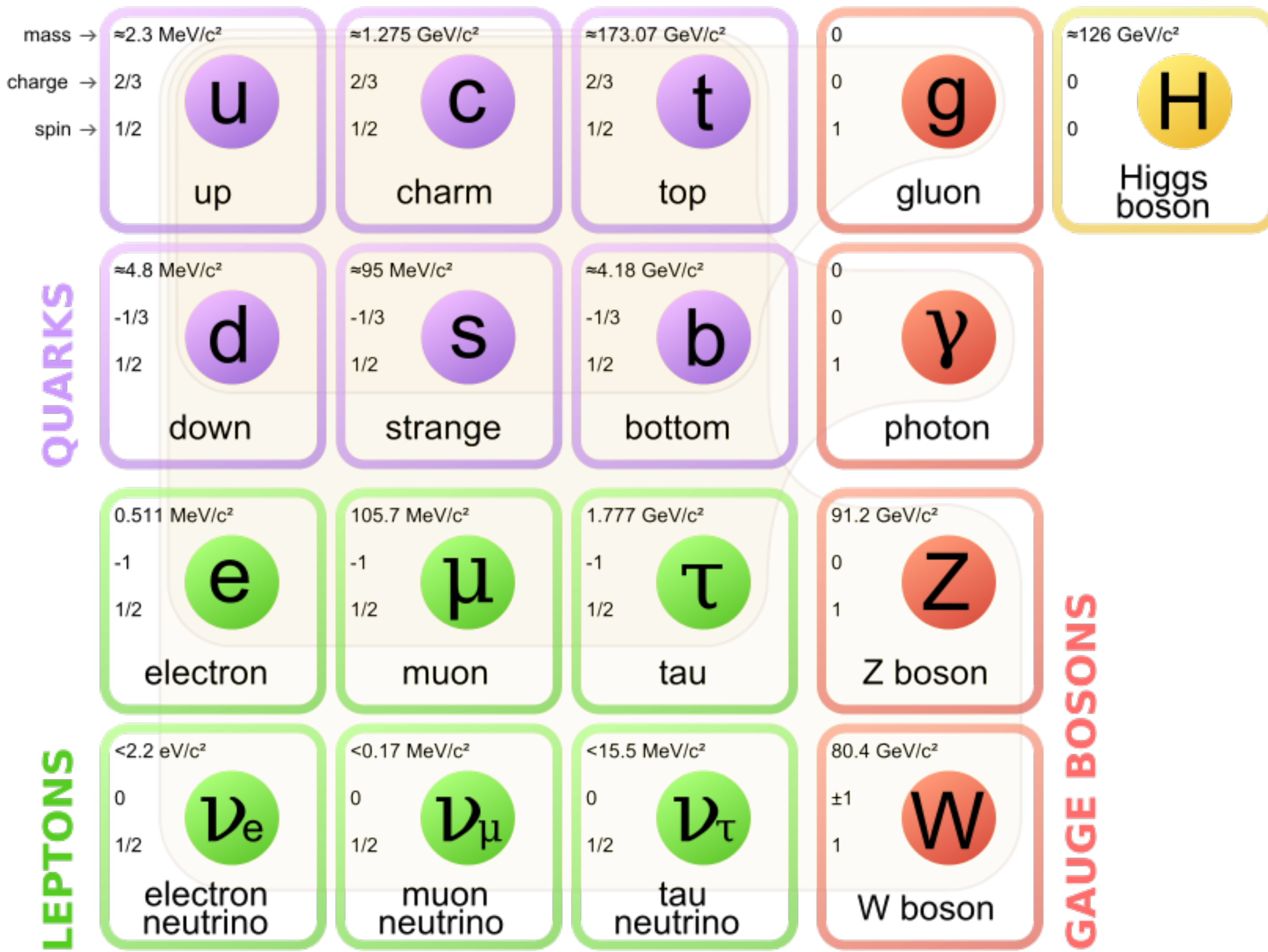
- **Photon**
- Mediates the EM force
- Responsible for Chemistry, Biology, and almost everything around us!
- U(1) symmetry

The force carriers



- W and Z bosons
- Mediates the weak force
- Only massive gauge bosons
- Responsible for radioactive decay
- SU(2) symmetry

The Standard Model

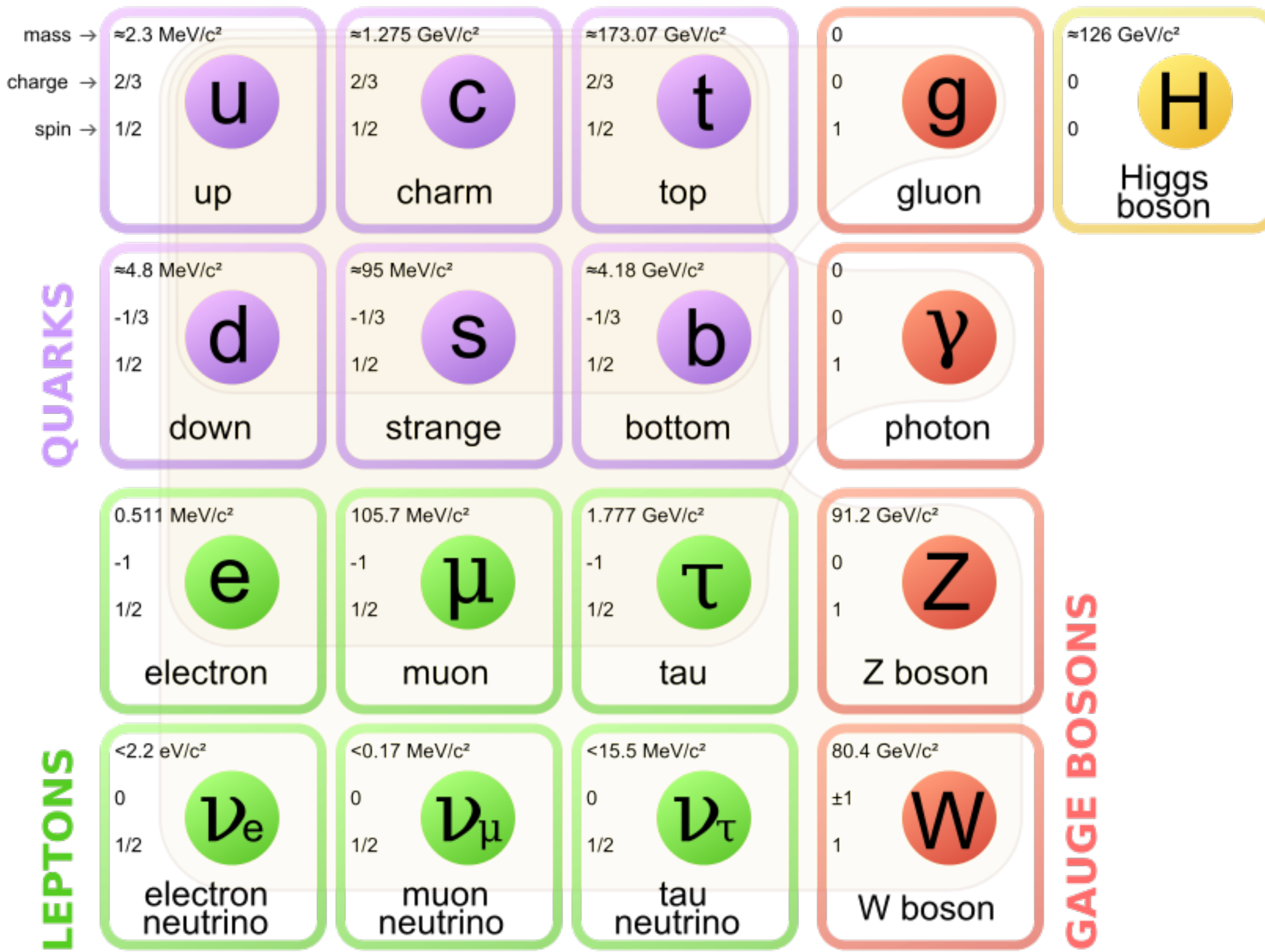


The Standard Model

- The ‘**Lagrangian**’ contains all the laws of physics in the Standard Model - all the particles and all the forces
- Particle physicists try to discover the Lagrangian of our universe

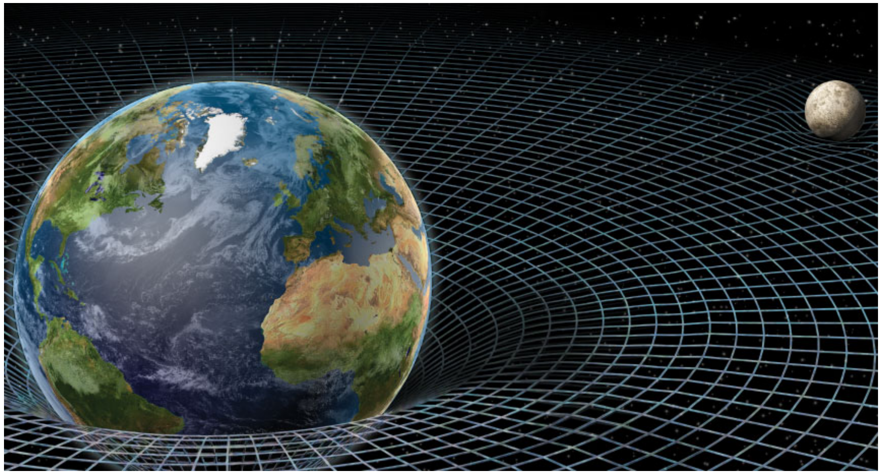
$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)} \\
& +(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + \text{(h.c.)} && \text{(lepton dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] && \text{(electron, muon, tauon mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right] && \text{(neutrino mass term)} \\
& +(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] && \text{(down, strange, bottom mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right] && \text{(up, charmed, top mass term)} \\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \quad (1)
\end{aligned}
$$

But what is missing?



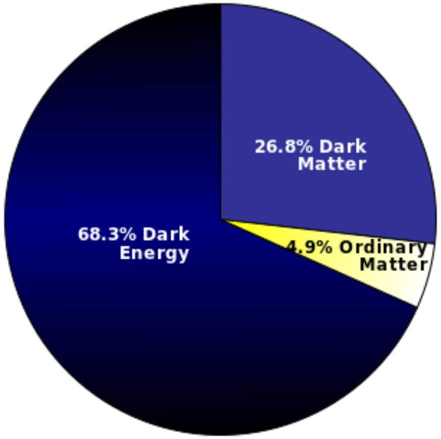
But what is missing?

- **GRAVITY!**
- General relativity used at the moment, but it is not quantum mechanical
- Graviton?



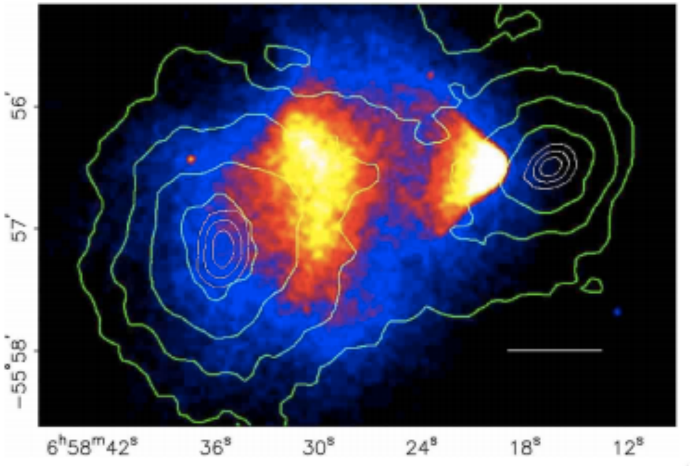
… What else?

… What else?



- Dark matter

- WIMPs (Weakly Interacting Massive Particles)



… Anything else?

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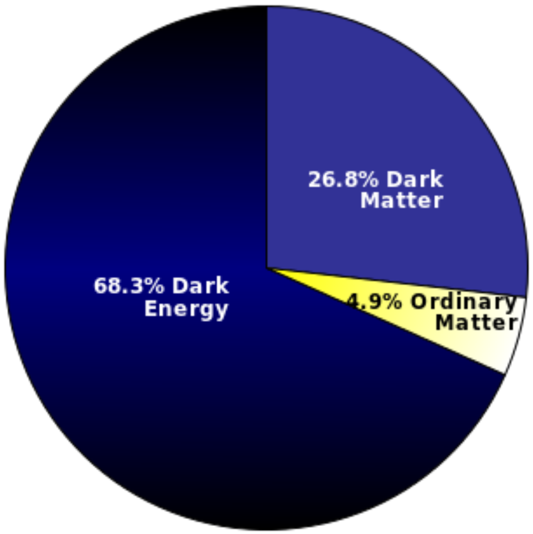

Other questions/problems

- 26 free parameters!

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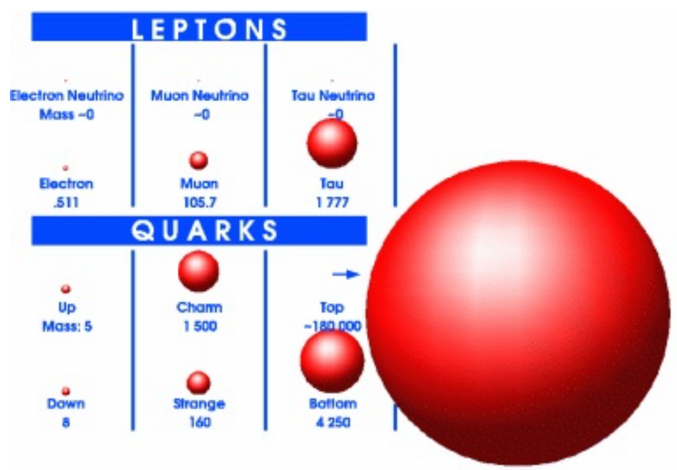
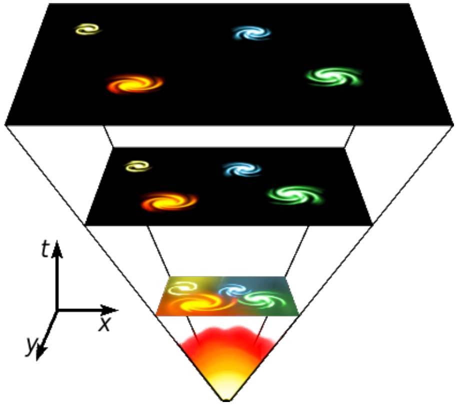
- Why three generations? And why do they get heavier?

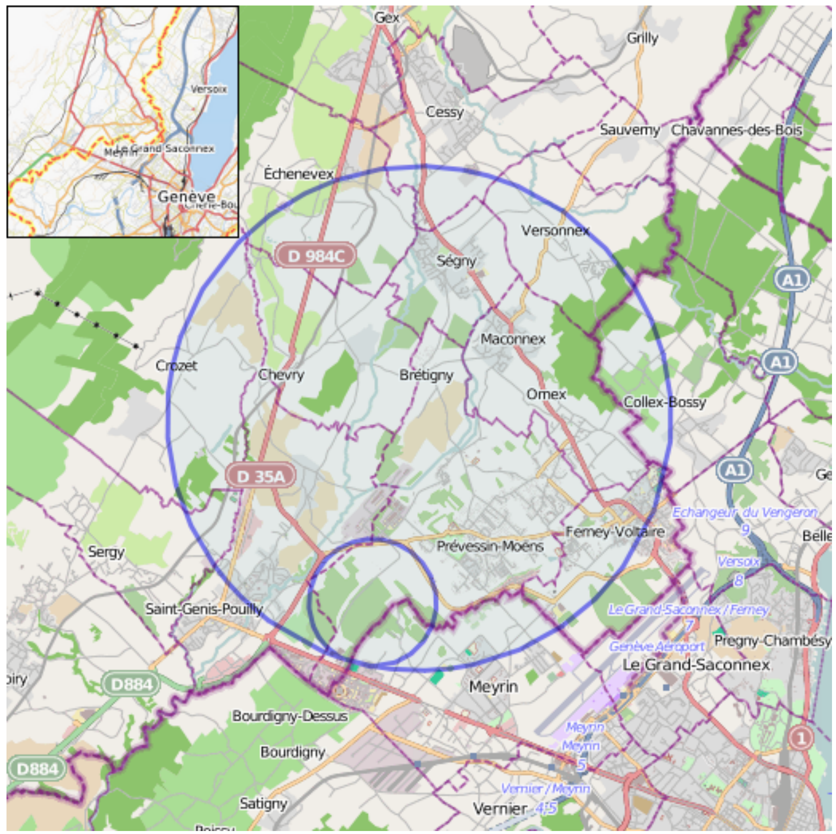


Other questions/problems

- 26 free parameters!
- Why three generations? And why do they get heavier?
- Where did all the anti-matter go?

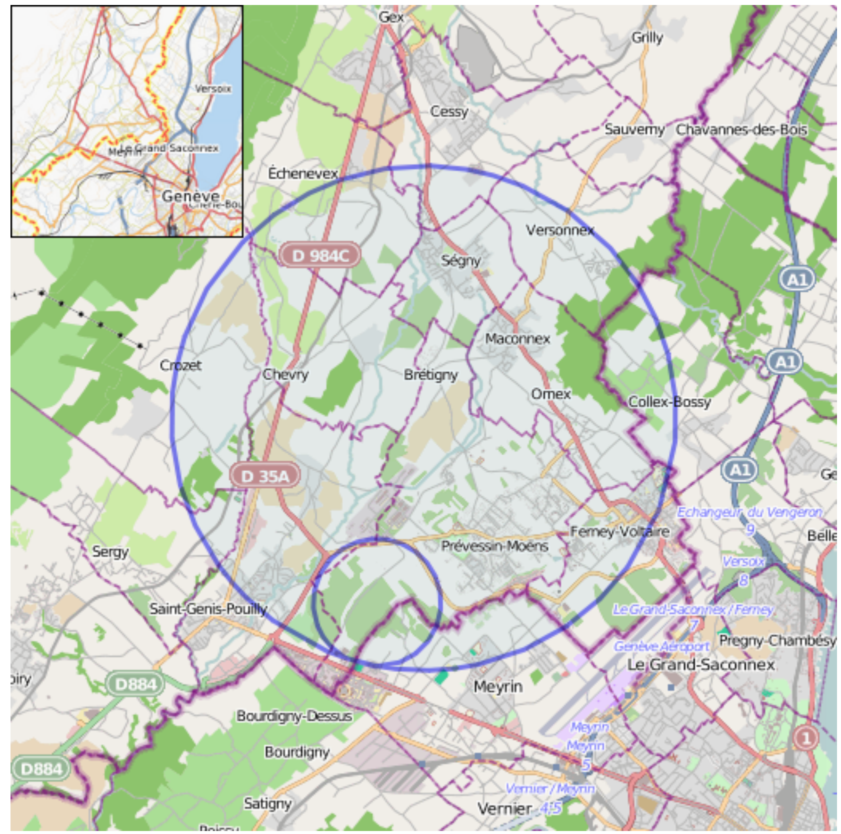


The Large Hadron Collider



Why such big colliders?

- LHC is **27 km** in circumference, to (eventually) get to energies of 14 TeV



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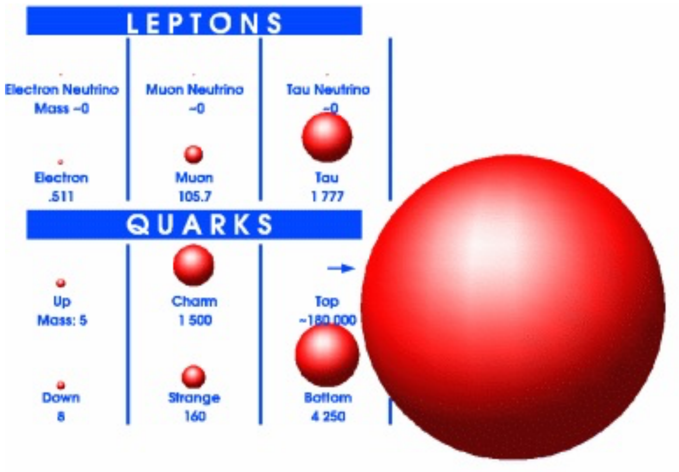

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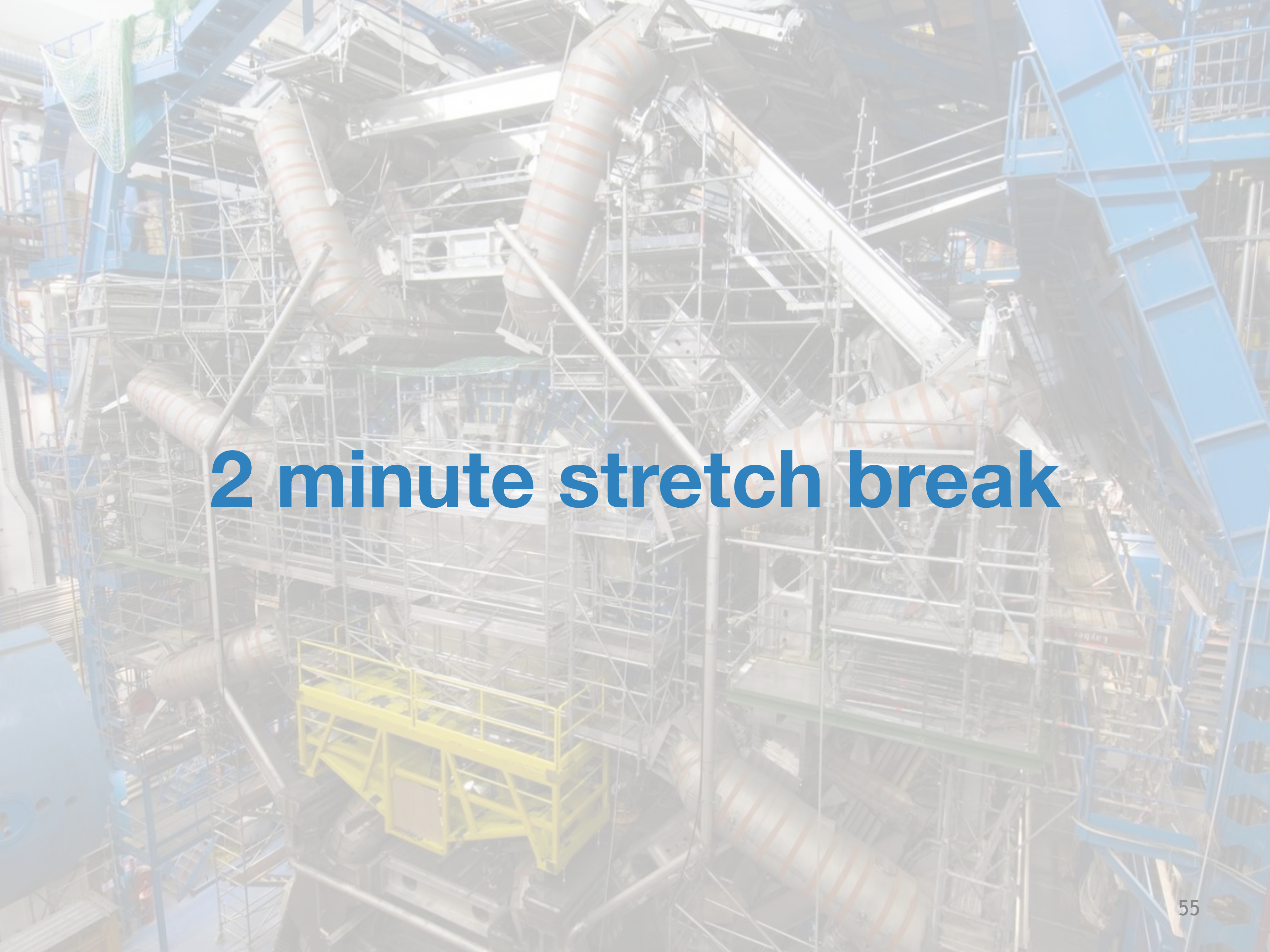
- $E=mc^2$
- $E=k_BT$

Time Machine

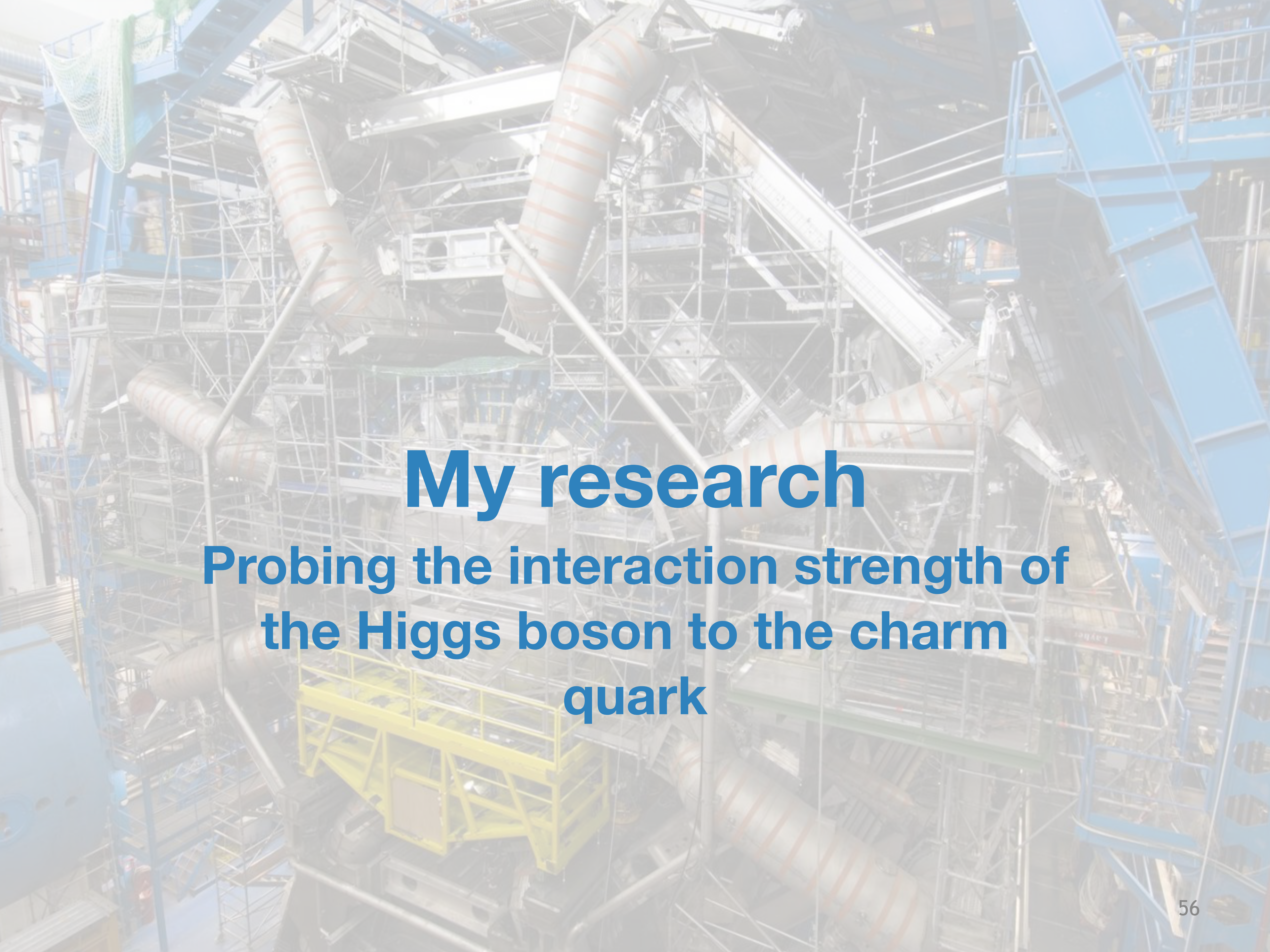
Why such big colliders?

- LHC is **27 km** in circumference, to (eventually) get to energies of 14 TeV
- $E=mc^2$
- $E=k_BT$
- $\Delta x \sim hc/4\pi E$

Any questions?



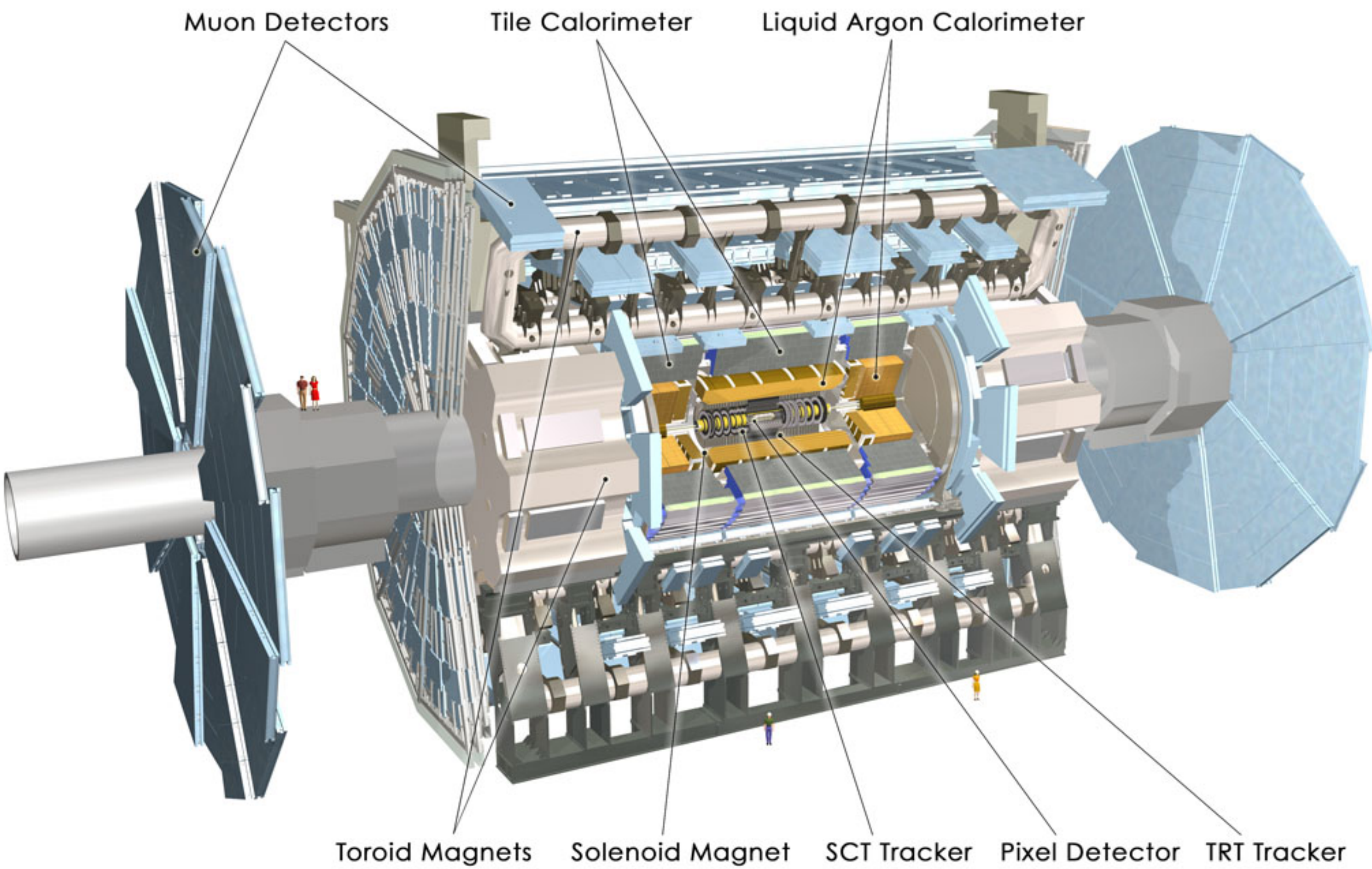
2 minute stretch break



My research

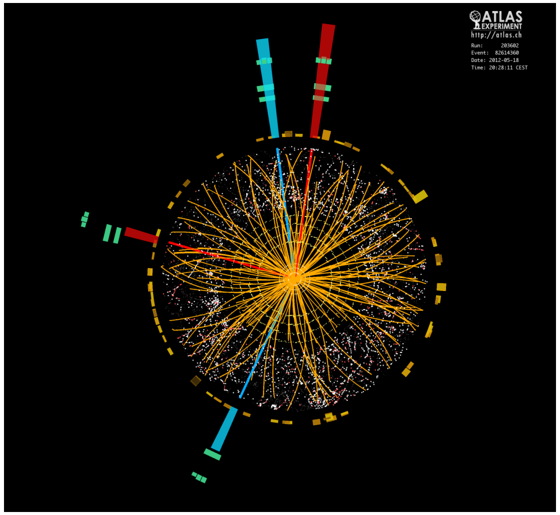
Probing the interaction strength of the Higgs boson to the charm quark

The ATLAS detector



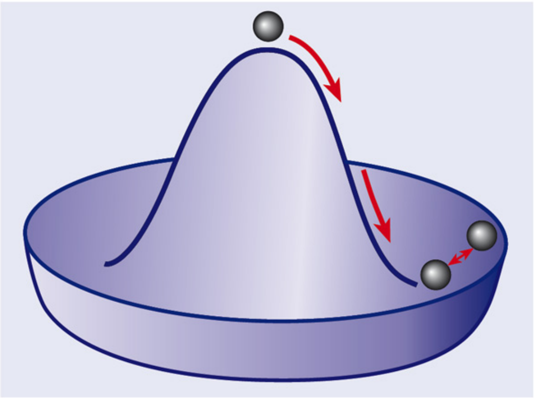
The Higgs boson

- A **NEW** fundamental particle and interaction



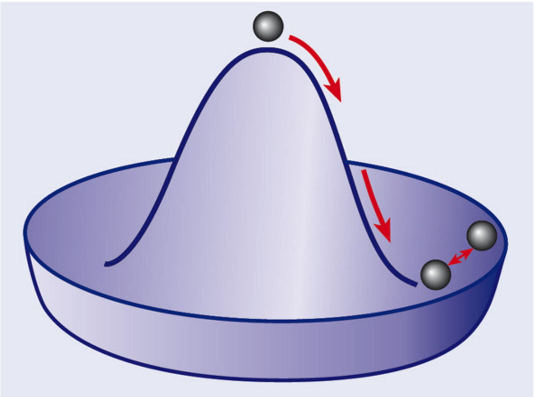
The Higgs boson

- A **NEW** fundamental particle and interaction
- Electroweak symmetry breaking



The Higgs boson

- A **NEW** fundamental particle and interaction
- Electroweak symmetry breaking
- Generates mass



The Higgs boson

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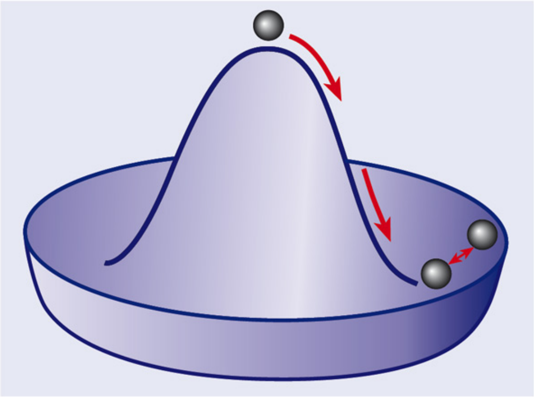
- Electroweak symmetry breaking
- Generates mass
- Non-zero vacuum expectation value



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- A **NEW** fundamental particle and interaction
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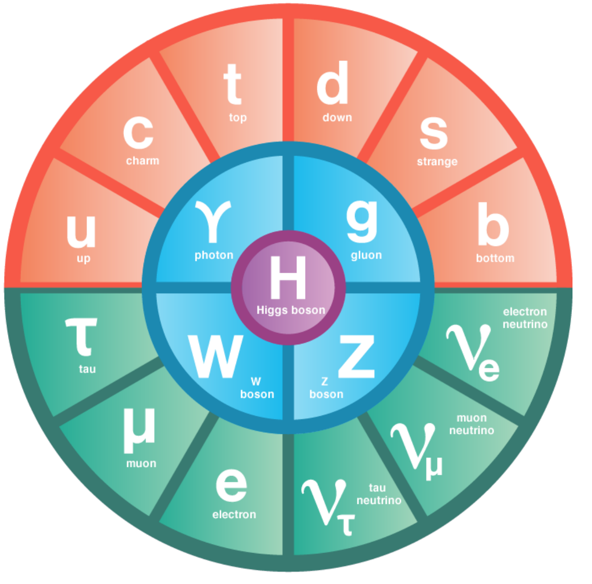
- Only spin-0 particle

The Higgs boson

- A **NEW** fundamental particle and interaction
- Electroweak symmetry breaking
- Generates mass
- Non-zero vacuum expectation value
- Only spin-0 particle
- Completes the Standard Model



My research

1. Searching for Higgs boson decays to non–Standard Model particles

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Search for Higgs boson decays to beyond-the-Standard-Model light bosons in four-lepton events with the ATLAS detector at $\sqrt{s} = 13$ TeV

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: A search is conducted for a beyond-the-Standard-Model boson using events where a Higgs boson with mass 125 GeV decays to four leptons ($\ell = e$ or μ). This decay is presumed to occur via an intermediate state which contains one or two on-shell, promptly decaying bosons: $H \to ZX/XX \to 4\ell$, where X is a new vector boson Z_d or pseudoscalar a with mass between 1 and 60 GeV. The search uses pp collision data collected with the ATLAS detector at the LHC with an integrated luminosity of 36.1 fb^{-1} at a centre-of-mass energy $\sqrt{s} = 13$ TeV. No significant excess of events above Standard Model background predictions is observed; therefore, upper limits at 95% confidence level are set on model-independent fiducial cross-sections, and on the Higgs boson decay branching ratios to vector and pseudoscalar bosons in two benchmark models.

KEYWORDS: Beyond Standard Model, Hadron-Hadron scattering (experiments)

ARXIV EPRINT: 1802.03388

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JHEP06(2018)166

PHYSICAL REVIEW LETTERS **125,** 221802 (2020)

Search for Higgs Boson Decays into a *Z* Boson and a Light Hadronically Decaying Resonance Using 13 TeV *pp* Collision Data from the ATLAS Detector

G. Aad *et al.*[*]
(ATLAS Collaboration)

(Received 7 April 2020; accepted 9 October 2020; published 25 November 2020)

A search for Higgs boson decays into a Z boson and a light resonance in two-lepton plus jet events is performed, using a pp collision dataset with an integrated luminosity of 139 fb^{-1} collected at $\sqrt{s} =$ 13 TeV by the ATLAS experiment at the CERN LHC. The resonance considered is a light boson with a mass below 4 GeV from a possible extended scalar sector or a charmonium state. Multivariate discriminants are used for the event selection and for evaluating the mass of the light resonance. No excess of events above the expected background is found. Observed (expected) 95% confidence-level upper limits are set on the Higgs boson production cross section times branching fraction to a Z boson and the signal resonance, with values in the range 17–340 pb (16^{+6}_{-5}–320^{+130}_{-90} pb) for the different light spin-0 boson mass and branching fraction hypotheses, and with values of 110 and 100 pb (100^{+40}_{-30} and 100^{+40}_{-30} pb) for the η_c and J/ψ hypotheses, respectively.

DOI: 10.1103/PhysRevLett.125.221802

The structure of the standard model (SM) scalar sector is the subject of intense scrutiny by the ATLAS [1] and CMS [2] Collaborations at the CERN Large Hadron Collider (LHC) [3]. At the current level of precision, all of the measured properties of the Higgs boson (H) [4,5] are found to be consistent with their SM predictions [6–10], and no additional Higgs boson has been observed to date. However, given the small natural decay width of the Higgs boson, even small additional contributions from physics beyond the SM can lead to final states with substantial, and thus possibly detectable, branching fractions ($\mathcal{B}$) [11]. This Letter presents a search for Higgs boson decays into a Z boson and a hadronically decaying light resonance in events with a same-flavor lepton pair (electrons or muons) and a jet in the ATLAS detector. Hadronic decays of an η_c or of a J/ψ charmonium resonance (Q), or of a light spin-0 boson from an extended Higgs sector with a mass up to 4 GeV, are considered and are reconstructed as a single jet.

The Yukawa sector of the SM [12] does not provide an explanation for the observed fermion mass hierarchy. As a result, a wide range of new physics scenarios have been proposed, including the Froggatt-Nielsen mechanism [13] and the Higgs-dependent Yukawa couplings model [14]; for a recent overview, see Ref. [15]. The couplings of the Higgs boson to the third-generation fermions [16–21] have been observed, and a program to probe its couplings to the first- and second-generation charged leptons has been established [22–25]. For its couplings to first- and second-generation quarks, several approaches are being explored. Focusing on the Higgs boson's coupling to the charm quark, direct searches have been performed for Higgs boson decays into charm quarks [26,27] and for exclusive decays into a J/ψ and a photon [28,29], with no excess observed. Constraints from differential cross section measurements of Higgs boson production versus transverse momentum (p_T) have also been derived [30,31]. Higgs boson decays into a gauge boson and a charmonium state, including an η_c or a J/ψ, have been proposed as another way to access the coupling of the Higgs boson to the charm quark [32–34] and to probe the nature of the Higgs boson [35]. This search follows the last approach and maximizes the signal acceptance by focusing on inclusive hadronic final states of the mesons in $H \to Z\eta_c$ and $H \to ZJ/\psi$ decays, which have SM branching fractions of 1.4×10^{-5} and 2.2×10^{-6} [35], respectively.

While the SM posits a single complex Higgs doublet field [36,37], extended Higgs sectors are motivated [38] and provide a rich phenomenology of additional scalars. Two such models discussed here are the two-Higgs-doublet model (2HDM) [11,39] and the 2HDM with an additional scalar singlet (2HDM + S) [11,40]. These represent two of the simplest extensions of the scalar sector, and with their type-II fermion couplings they are necessary to generate the masses in the minimal supersymmetric SM and the next-to-minimal supersymmetric SM, respectively [41]. Both of these models can include additional light pseudoscalars (a) with significant $\mathcal{B}(H \to Za)$ or $\mathcal{B}(H \to aa)$ [11]. In the

[*]Full author list given at the end of the article.

0031-9007/20/125(22)/221802(22) 221802-1

My research

1. Searching for Higgs boson decays to non–Standard Model particles
2. Probing the interaction strength between the Higgs boson and the charm quark

PHYSICAL REVIEW LETTERS **120,** 211802 (2018)

Search for the Decay of the Higgs Boson to Charm Quarks with the ATLAS Experiment

M. Aaboud *et al.*[*]
(ATLAS Collaboration)

(Received 14 February 2018; published 22 May 2018)

A direct search for the standard model Higgs boson decaying to a pair of charm quarks is presented. Associated production of the Higgs and Z bosons, in the decay mode $ZH \to \ell^+\ell^- c\bar{c}$ is studied. A data set with an integrated luminosity of 36.1 fb^{-1} of pp collisions at $\sqrt{s} = 13\mathrm{TeV}$ recorded by the ATLAS experiment at the LHC is used. The $H \to c\bar{c}$ signature is identified using charm-tagging algorithms. The observed (expected) upper limit on $\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c})$ is 2.7 ($3.9^{+2.1}_{-1.1}$) pb at the 95% confidence level for a Higgs boson mass of 125 GeV, while the standard model value is 26 fb.

DOI: 10.1103/PhysRevLett.120.211802

In July 2012, the ATLAS and CMS collaborations announced the discovery of a new particle with a mass of approximately 125 GeV [1,2] in searches for the standard model (SM) Higgs boson at the Large Hadron Collider (LHC) [3]. Subsequent measurements indicate that this particle is consistent with the SM Higgs boson [4–10]. Direct evidence for the Yukawa coupling of the Higgs boson to the top [11] and bottom [12,13] quarks was recently obtained. Measurements of the Yukawa coupling of the Higgs boson to quarks in generations other than the third are difficult at hadron colliders, due to small branching fractions, large backgrounds, and challenges in jet flavor identification [14,15]. This Letter presents a direct search by the ATLAS experiment for the decay of the Higgs boson to a pair of charm (c) quarks. This search targets the production of the Higgs boson in association with a Z boson decaying to charged leptons: $Z(\ell^+\ell^-)H(c\bar{c})$, where $\ell = e, \mu$.

The SM branching fraction for a Higgs boson with a mass of 125 GeV to decay to a pair of charm quarks is predicted to be 2.9% [16]. The inclusive cross section for $\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c})$ is 26 fb at $\sqrt{s} = 13$ TeV [17]. Rare exclusive decays of the Higgs boson to a light vector meson or quarkonium state and a photon can also probe the couplings of the second-generation quarks to the Higgs boson [18–21]. Previously, the ATLAS Collaboration presented an indirect search for the decay of the Higgs boson to c quarks via the decay to $J/\psi\gamma$, obtaining a branching fraction limit of 1.5×10^{-3} at the 95% confidence level (C.L.), which approximately corresponds to a limit of 540 times the SM branching fraction prediction [14,20]. Bounds on the Higgs boson branching fractions to unobserved final states and fits to global rates constrain $\mathcal{B}(H \to c\bar{c}) < 20\%$ at the 95% C.L., assuming SM production cross sections [22]. These limits can still accommodate large modifications to the Higgs boson coupling to charm quarks from new physics [22]. In this Letter, a new approach is introduced to investigate the coupling of the Higgs boson to charm quarks.

The search is performed using pp collision data recorded in 2015 and 2016 with the ATLAS detector [23] at $\sqrt{s} = 13$ TeV. The ATLAS detector at the LHC covers nearly the entire solid angle around the collision point [24]. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroidal magnets. An additional pixel layer was installed for the $\sqrt{s} = 13$ TeV running period [25]. After the application of beam, detector, and data-quality requirements, the integrated luminosity corresponds to $36.1 \pm 0.8\ \mathrm{fb}^{-1}$, measured following Ref. [26]. Events are required to contain exactly two same-flavor leptons with an invariant mass consistent with that of the Z boson, and at least two jets of which one or two are identified as charm jets (c jets). In this Letter, lepton refers to only electrons or muons. The analysis procedure is validated by measuring the yield of ZW and ZZ production, where the sample is enriched in $W \to cs$, cd and $Z \to c\bar{c}$ decays. Further details can be found in Ref. [12].

Monte Carlo (MC) simulated samples were produced for signal and background processes using the full ATLAS detector simulation [27] using GEANT4 [28]. Table I provides details of the event generators used for each signal and background sample. Signal events were produced at next-to-leading order (NLO) for the $q\bar{q} \to ZH$ process and at leading order (LO) for the $gg \to ZH$ process with POWHEG-BOX v2 [32]. The dominant $Z +$ jets background and the resonant diboson ZW and ZZ processes were generated using SHERPA 2.2.1 [54]. The $t\bar{t}$ background was

[*]Full author list given at the end of the article.

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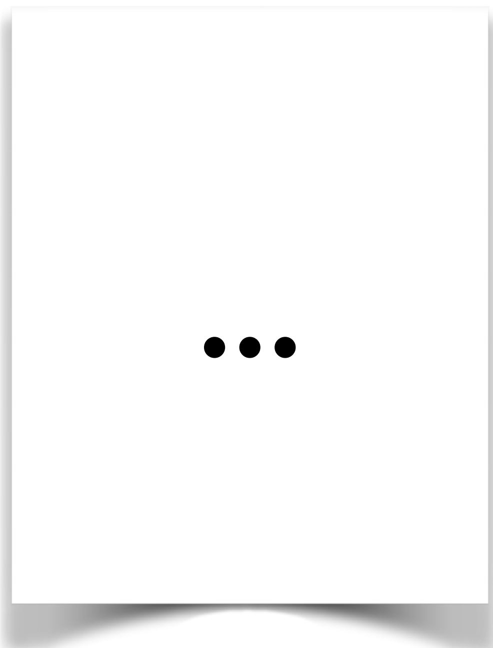
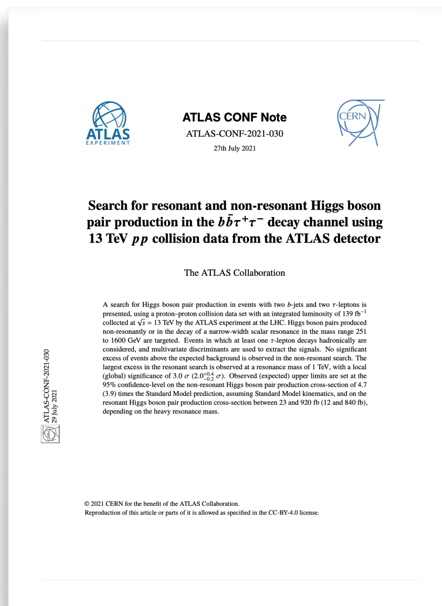


My research

1. Searching for Higgs boson decays to non–Standard Model particles
2. Probing the interaction strength between the Higgs boson and the charm quark
3. Probing the interaction strength between the Higgs boson and itself


ATLAS CONF Note
ATLAS-CONF-2021-030
27th July 2021

Search for resonant and non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ decay channel using 13 TeV pp collision data from the ATLAS detector

The ATLAS Collaboration

A search for Higgs boson pair production in events with two b-jets and two τ-leptons is presented, using a proton–proton collision data set with an integrated luminosity of 139 fb^{-1} collected at $\sqrt{s}$ = 13 TeV by the ATLAS experiment at the LHC. Higgs boson pairs produced non-resonantly or in the decay of a narrow-width scalar resonance in the mass range 251 to 1600 GeV are targeted. Events in which at least one τ-lepton decays hadronically are considered, and multivariate discriminants are used to extract the signals. No significant excess of events above the expected background is observed in the non-resonant search. The largest excess in the resonant search is observed at a resonance mass of 1 TeV, with a local (global) significance of 3.0 σ ($2.0^{+0.4}_{-0.2}$ σ). Observed (expected) upper limits are set at the 95% confidence-level on the non-resonant Higgs boson pair production cross-section of 4.7 (3.9) times the Standard Model prediction, assuming Standard Model kinematics, and on the resonant Higgs boson pair production cross-section between 23 and 920 fb (12 and 840 fb), depending on the heavy resonance mass.

ATLAS-CONF-2021-030
29 July 2021

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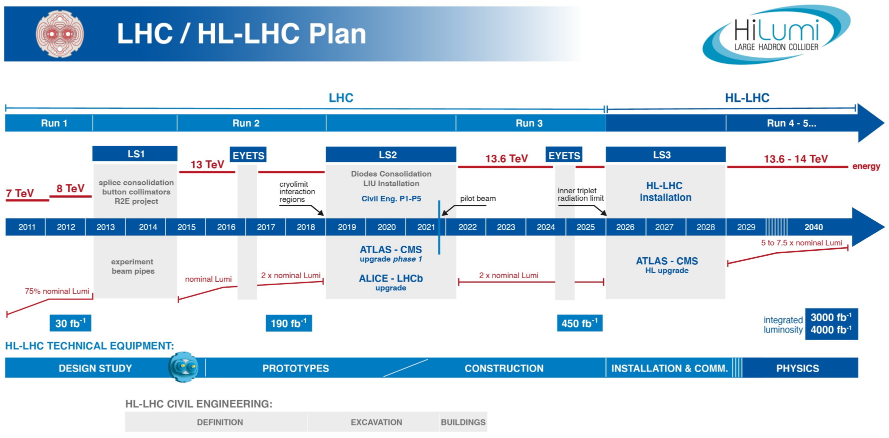
4. Work on the upgrade of the ATLAS detector



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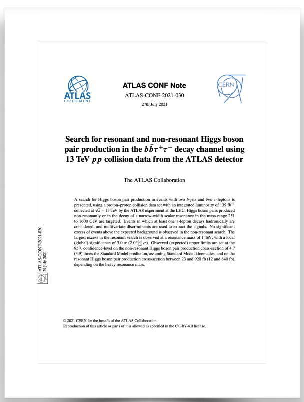

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- Ad hoc: no explanation of masses, and no underlying symmetry principle

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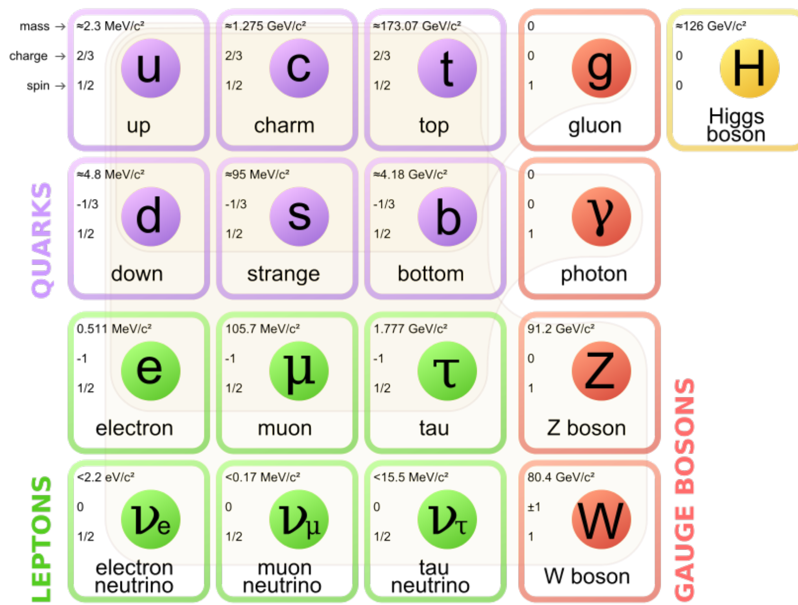
- Why three generations? And why do they get heavier?



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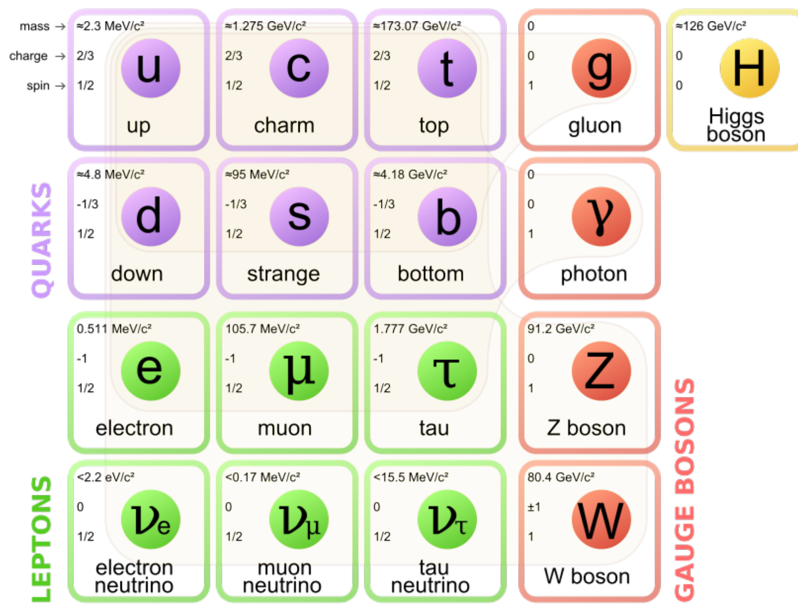

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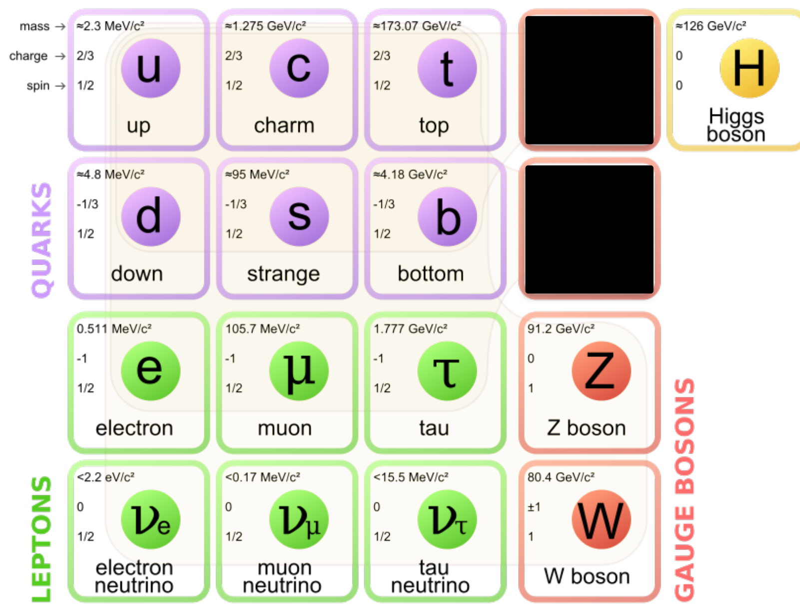

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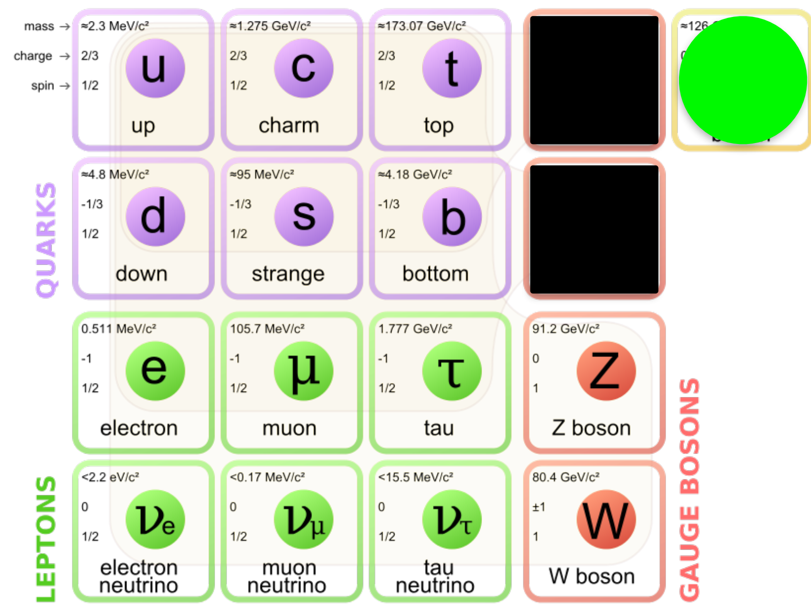

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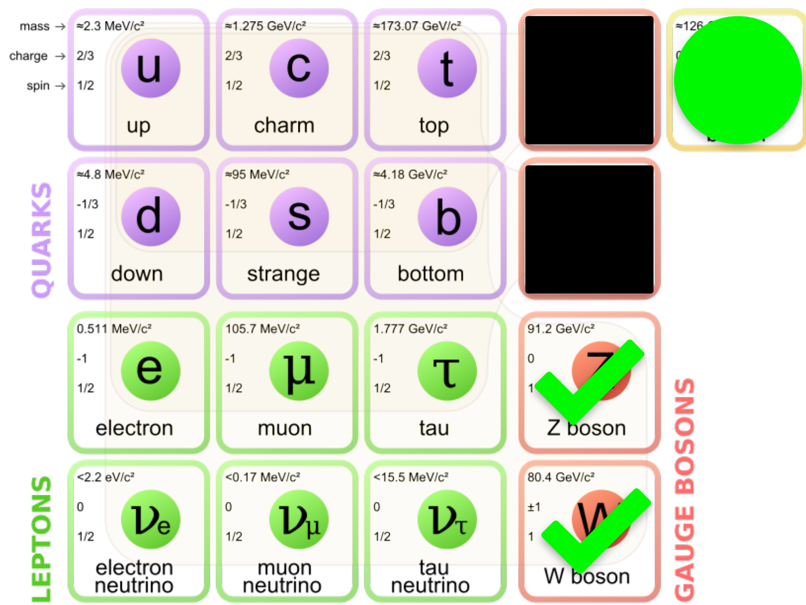

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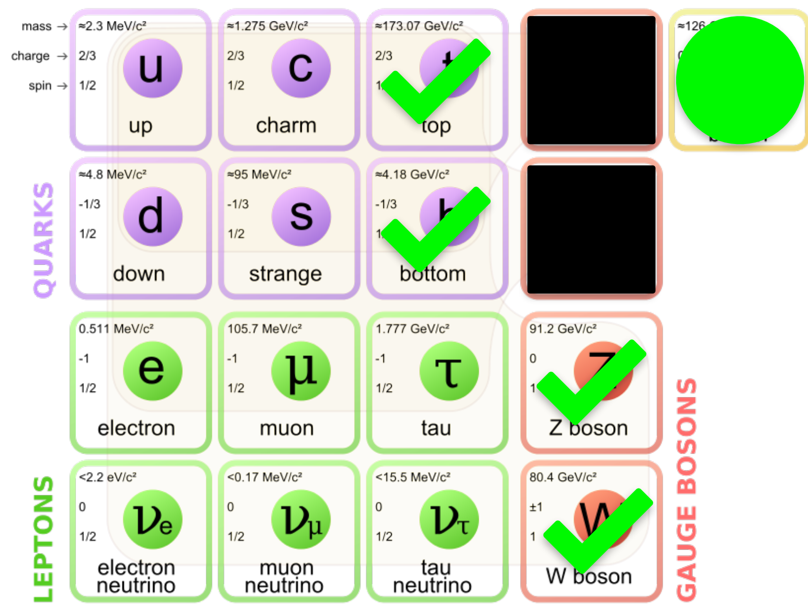

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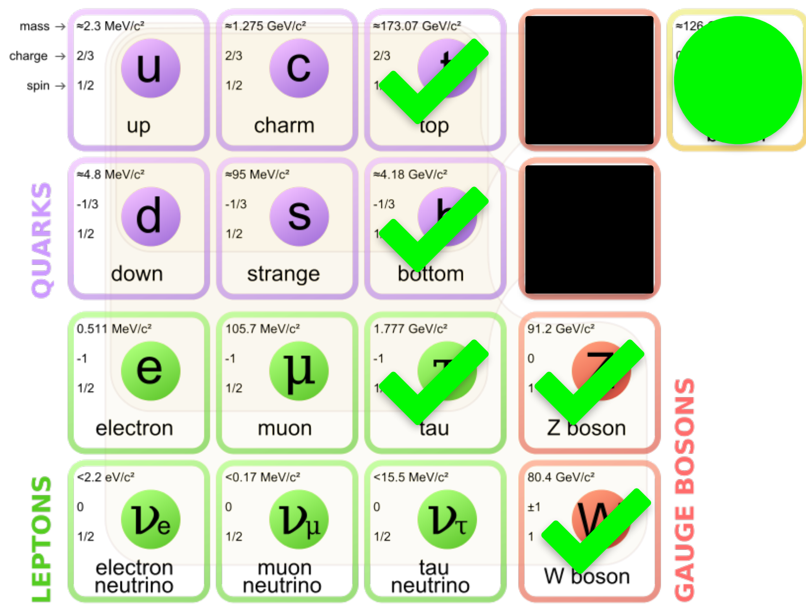

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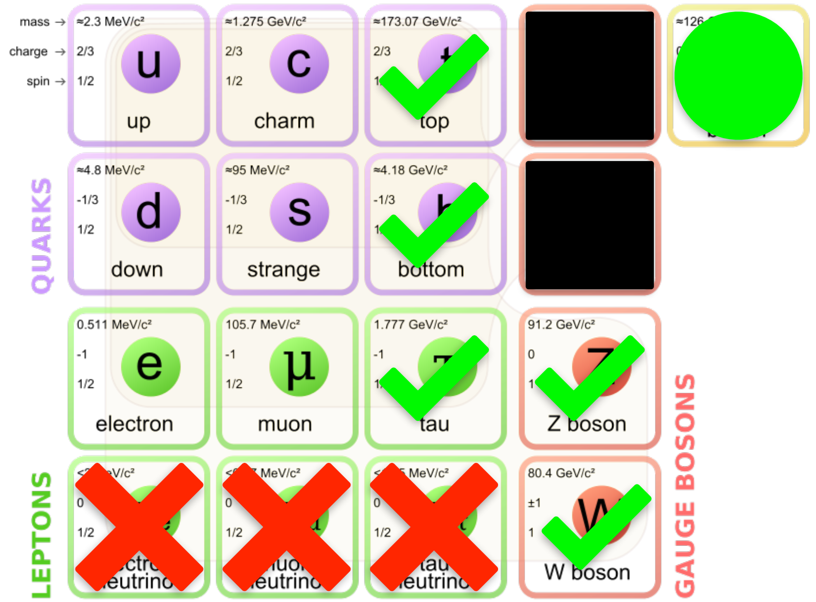

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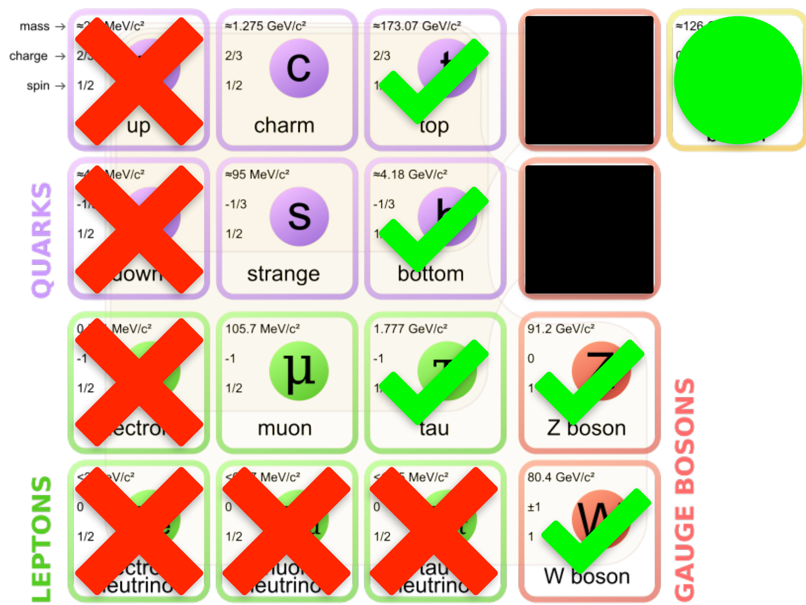

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- To find the **Theory of Everything!!!**

How to probe an interaction strength?

- There are lots of ways…
- The most direct ways are to measure physics processes that include the interaction

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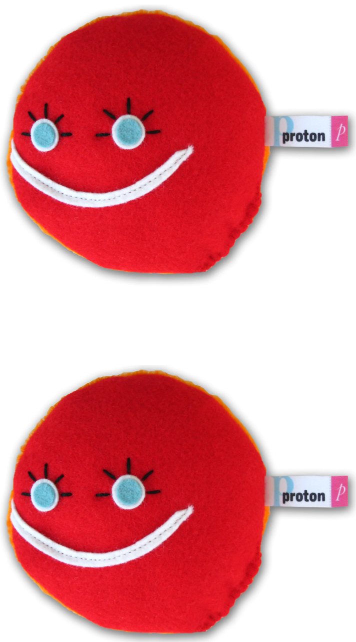
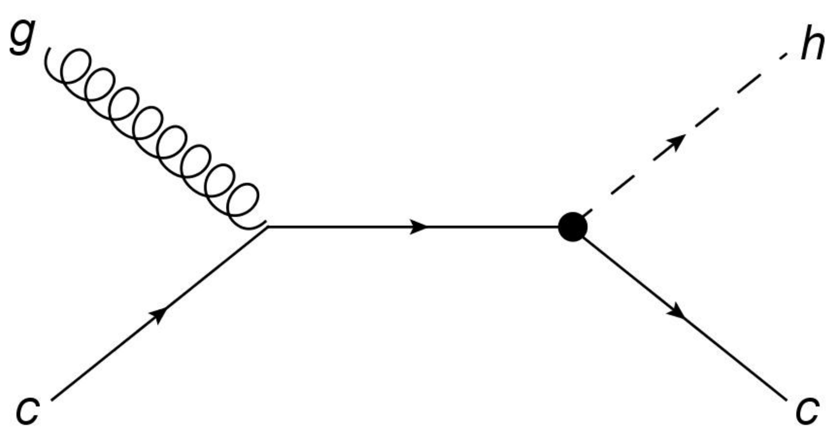
- The most direct ways are to measure physics processes that include the interaction
- You can measure the production:





PRL 115 (2015) 211801

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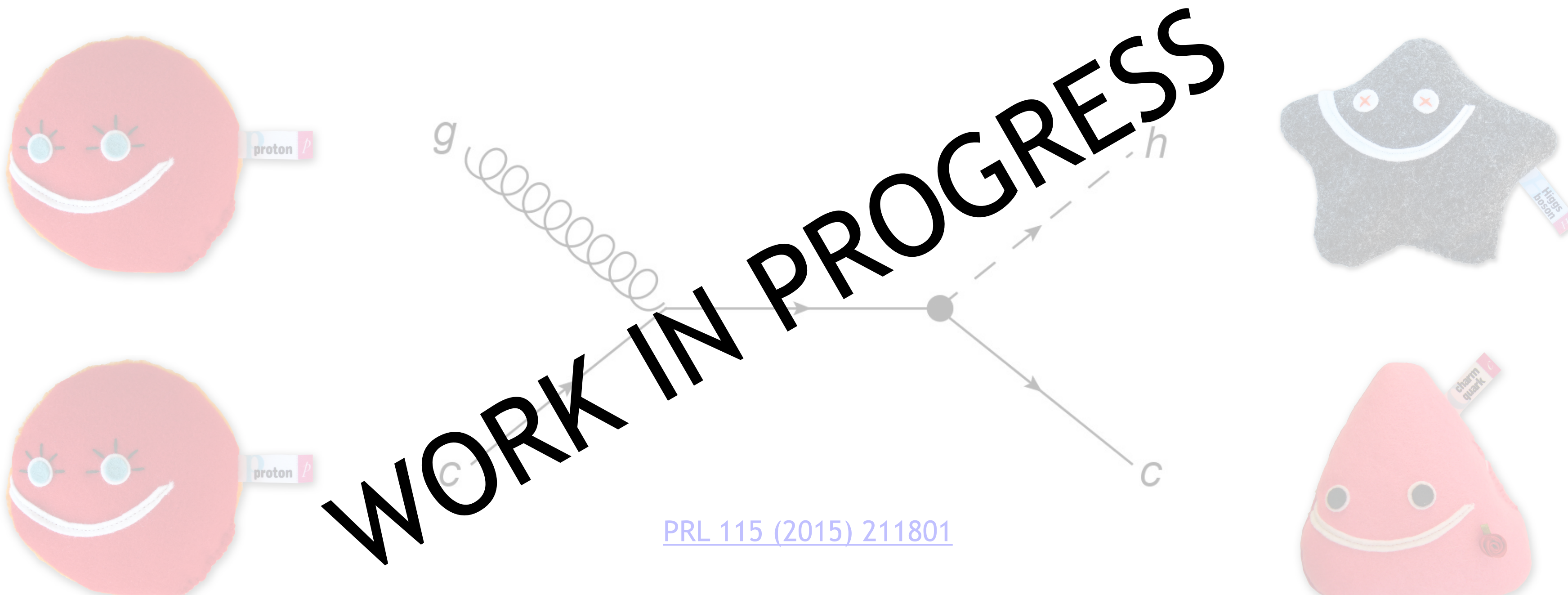

How to probe an interaction strength?

- There are lots of ways…
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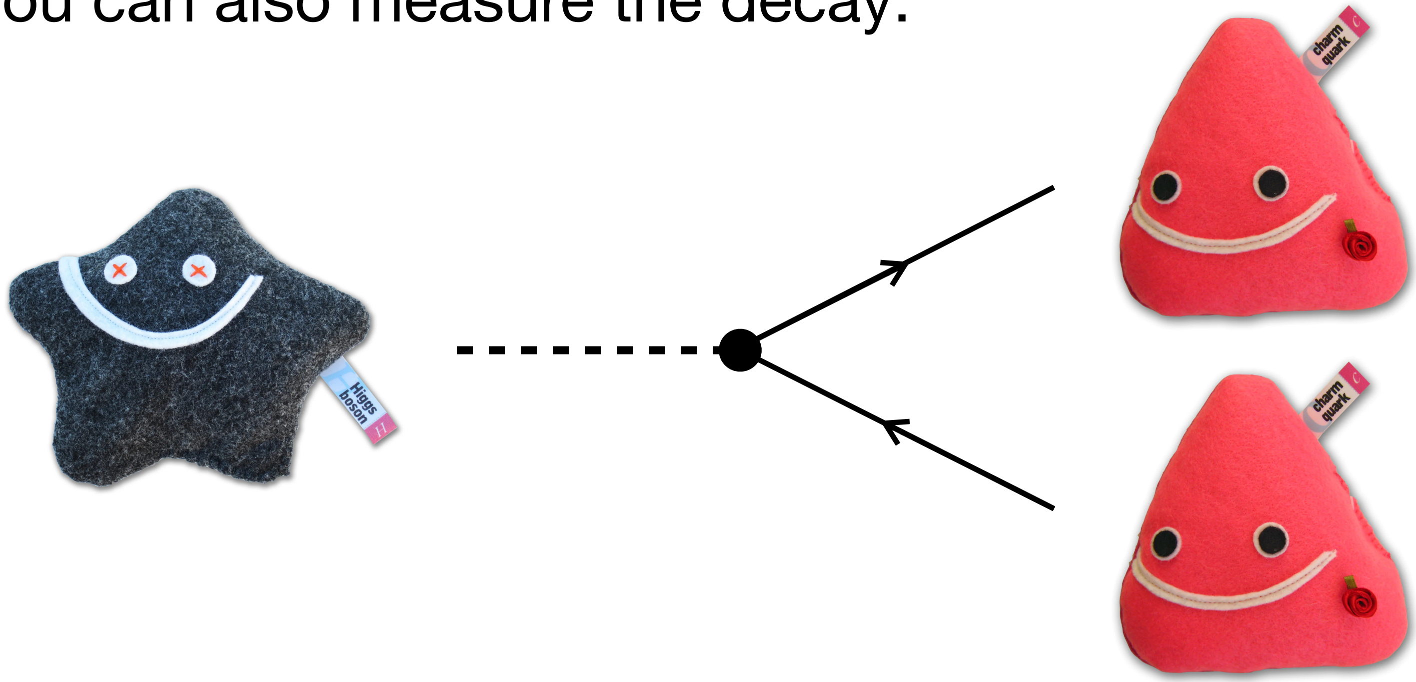
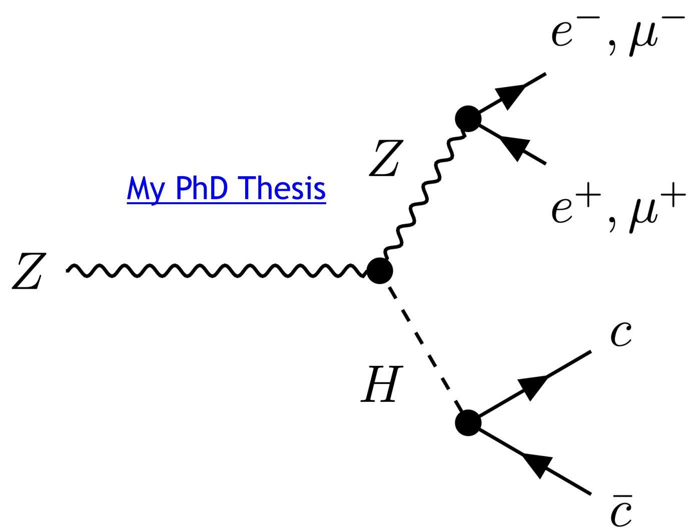
- You can measure the production
- You can also measure the decay:



ZH associated production

- Look for Higgs bosons produced in association with a Z boson

My PhD Thesis



PRL 120 (2018) 211802

ZH associated production

- Look for Higgs bosons produced in association with a Z boson
- Z boson decays to leptons are used to trigger the events

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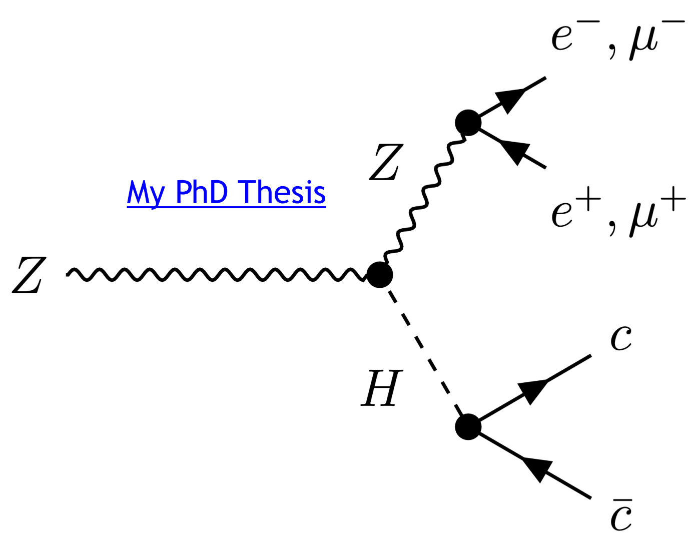

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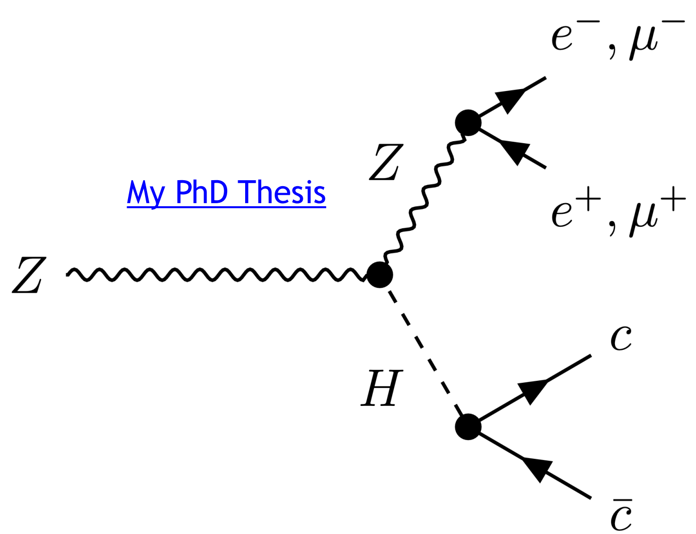
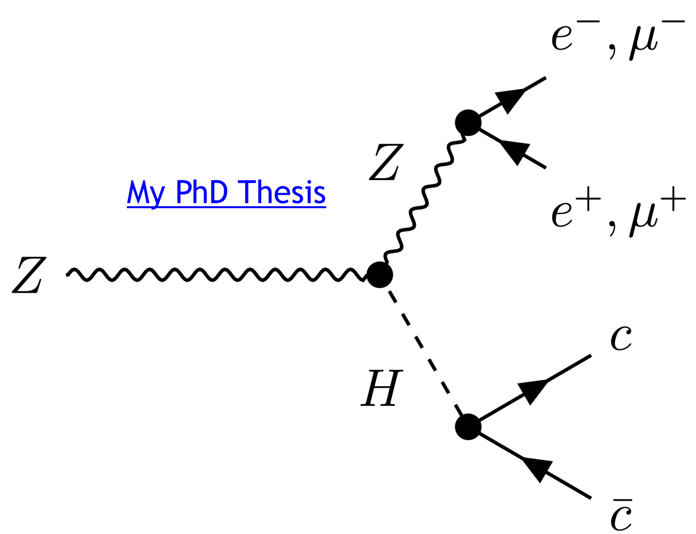


PRL 120 (2018) 211802

ZH associated production

- Look for Higgs bosons produced in association with a Z boson
- Z boson decays to leptons are used to trigger the events
- Reject massive background from jets
- Categorise events based on Z boson transverse momentum

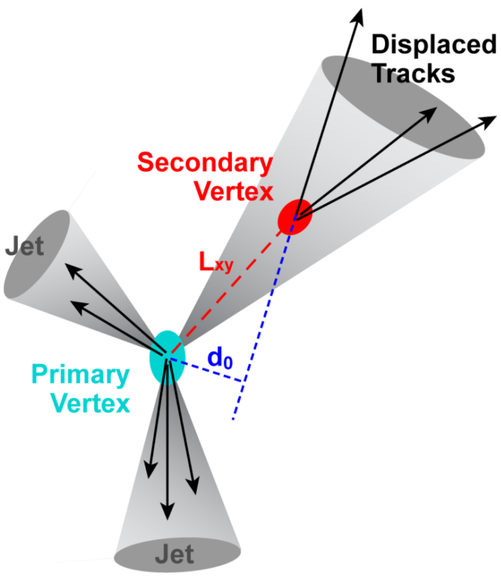
My PhD Thesis



PRL 120 (2018) 211802

Charm-Jet Tagging

- Particles containing charm quarks often drift away from the proton–proton interaction point before decaying
  - This leaves a distinctive signature in the inner tracking detector



Sketch from D0

PRL 120 (2018) 211802

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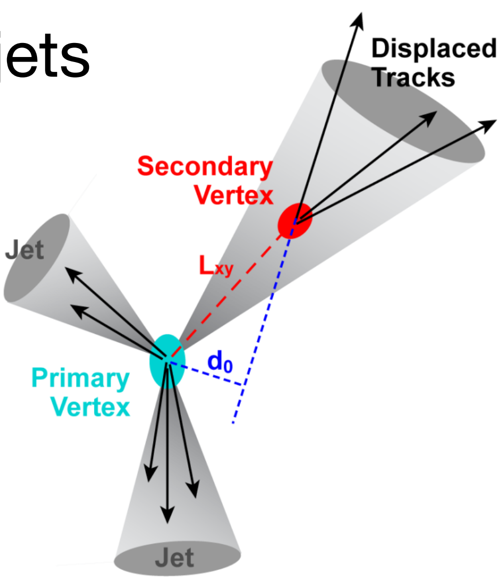

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PRL 120 (2018) 211802

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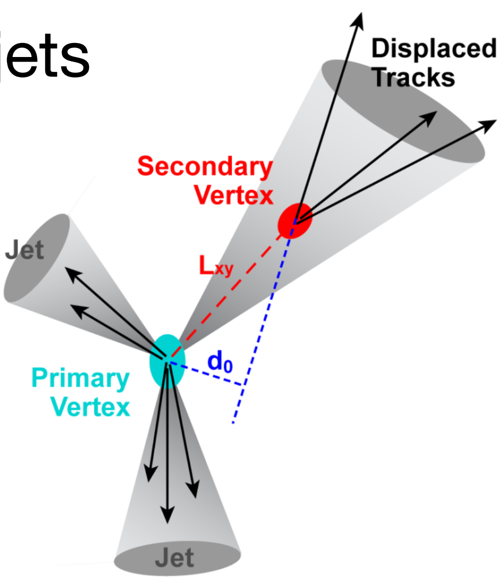
  - *c*-jet efficiency = 41%
  - Light flavour–jet rejection = 20
  - *b*-jet rejection = 4.0



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  - *c*-jet efficiency = 41%
  - Light flavour–jet rejection = 20
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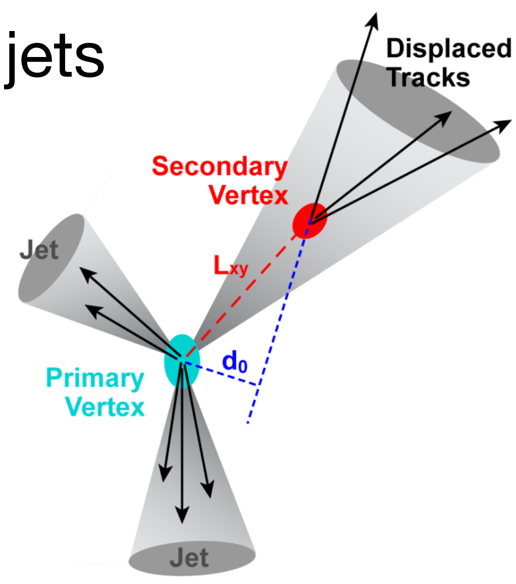
- 1 and 2 charm-tag categories used



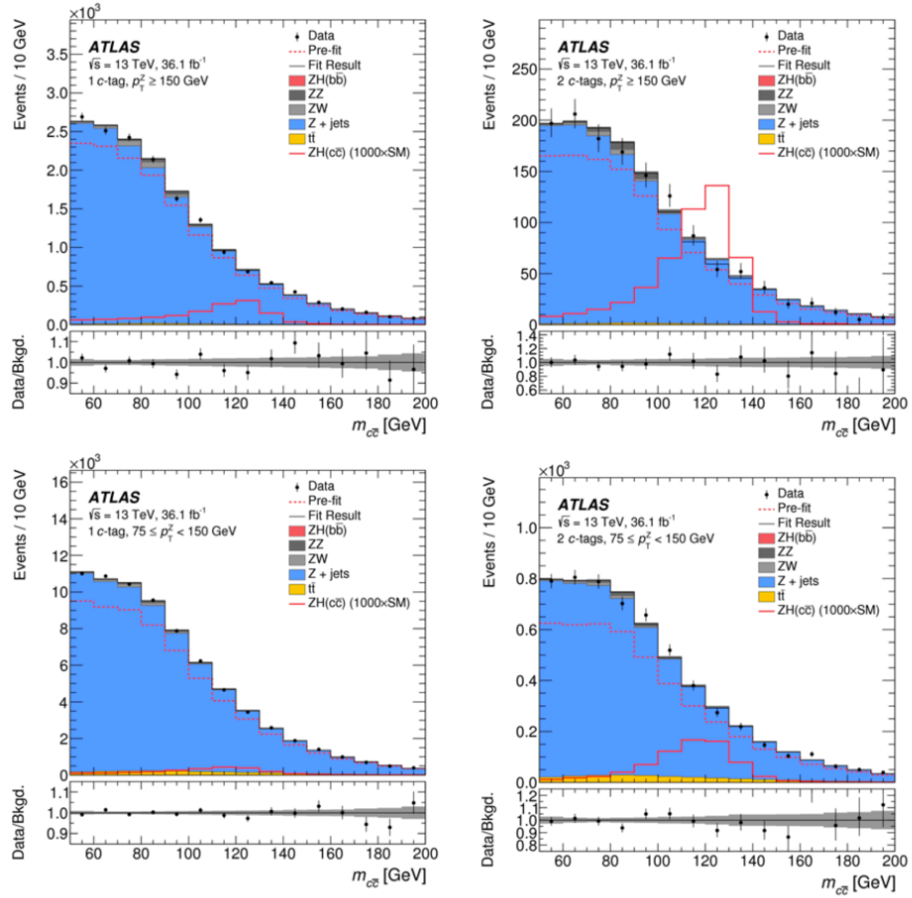
Sketch from D0

PRL 120 (2018) 211802

Results

1 c-tag | **2 c-tags**

Rows: $\frac{p_T^Z}{\mathrm{GeV}} > 150$ (top); $75 < \frac{p_T^Z}{\mathrm{GeV}} < 150$ (bottom)



PRL 120 (2018) 211802

Results

$$\sigma < 110 \times \sigma_{SM}$$

(95% confidence level)

PRL 120 (2018) 211802

Outlook

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- Will likely ultimately need to use both Higgs boson decays to charm quarks, and H+c production
- Hopefully more to come on H+c production very soon…

If you want to know more

- Find more information on the CERN and ATLAS websites
- See also the ATLAS and U.S. ATLAS outreach websites
- Keep up-to-date with many of the latest developments with the ATLAS Physics Briefings
- Also keep an eye out for the International Masterclass, and any upcoming ATLAS Virtual Visits
- “Overview for Non-Physicists” section of my PhD thesis
- And much more…

Thanks for listening!

Any questions?